THE UNIVERSITY OF ALBERTA

# A FLUIDIC TEMPERATURE REGULATOR

by

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The undersigned certify that they have read, and recomended to the Faculty of Graduate Studies for acceptance, a thesis entitled A Fluidic Temperature Regulator submitted by Karel Domas in partial fulfilment of the requirements for the degree of Master of Science.

## ABSTRACT

This thesis describes the design of a fluidic control system. A temperature controller was chosen as an example, to present the general ideas of the design philosophy. The circuits to accomplish each of the required operations are thoroughly discussed.

The design of the sensor as well as the design of the system itself, as presented in this thesis, is directly applicable to the other design objectives. These objectives could be a different range of regulated temperatures or a modified method of sensor installation. A comparison of fluidics with other logic devices is also discussed.

## ACKNOWLEDGEMENTS

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ERRATA

| Page | Line | Remarks |
|---|---|---|
| 59 | Fig.3.23 | For 20 msec/cm read 50 msec/cm |

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# CHAPTER 1

# INTRODUCTION

## Fluidics, the Present State of Art

Fluidics, today the most used name for devices producing amplification of signals transmitted by a fluid medium without the use of mechanical moving or deformable parts, is entering the second decade of its existence. At the early stages of development predictions were made that fluidics might oust electronic and electrical devices and systems. At present a more realistic approach is used. Although a unified theory has not been fully developed, long experience has taught what the advantages and limitations of fluidic devices are. During the past several years the promising advantages of fluidics caused many manufacturers to develop and produce fluidic devices and systems. On the other hand, electronics has made great strides ahead. Today, the designer considers the use of fluidics as one possible method of designing his system. Whether he chooses

fluidics or some other technique depends only partly on the required functions of his system. Reliability, sensitivity to severe environmental conditions, cost and complexity, among other features, must be taken into acount. While comparing fluidic logic techniques with other means of performing the same functions, the designer must take care to separate the basic functions from the means of implementing them. Fluidics is capable of performing all the logic functions which electrical, electronic, mechanical and moving part fluid control devices can perform. Fluidics cannot perform any functions which cannot be carried out by any other means (Ref. 12). Thus the choice of fluidics over another technique becomes a question of implementation rather than function. Implementation, in turn, is a matter of economics, or, in other words, potential advantage over other techniques.

Let us consider the advantages and disadvantages of fluidic devices more closely, since they are the factors which direct the designer's choice.

## Advantages of Fluidics

### 1. Reliability

The reliability of fluidic devices was predicted to exceed those of comparable electronic components by two orders of magnitude, since fluidic devices contain few or no moving parts to flex, stick or break. Therefore, the re-

liability problems caused by aging and wear are eliminated. The proper choice and quality of the working fluid and structural materials eliminates failures caused by dirt, deterioration and chemical reactions. Furthermore, many fluidic devices show ample tolerance to variations in the operating fluid parameters.

2. Operation under Extreme Environmental Conditions

Fluidic components can be fabricated from any solid material, but ceramics, metals, plastics and glass have proven to be most suitable. Depending on the material chosen, fluidic components can operate without malfunction under shock and vibration reaching magnitudes up to 1,000 G's and frequencies of 5,000 Hz and temperatures up to 3,000 or 4,000 degrees F. Fluidic systems can be integrated into solid blocks of metal or ceramics. Constant venting prevents the fluidic system from ingesting contaminants from the surrounding medium.

Connections and line-taps can be made or changed while the system is under power without the shock hazards inherent in electrical and electronic systems. Fluidic devices are insensitive to burn-out, shorting, or overloading. They are inherently explosion proof.

3. Resistance to Radiation

Fluidic devices neither generate nor are affected by radiation.

4. Low Cost

Similar to the situation in electronics, techniques are being developed to produce fluidic devices in large quantities economically. Mass production would reduce the cost of fluidic devices under the price of conventional comparable electronic products although the cost of integrated electronic circuits will always be lower.

## Disadvantages of Fluidics

1. Speed of Response

The switching times of fluidic devices are of the order of a millisecond and signal propagation times of about a millisecond per foot are typical for fluid flip-flops. Fluidics are most likely to compete with electromechanical relays in the area of industrial control such as machine tool control, automation equipment, packaging machines and the like.

2. Cross-coupling Effects

Interconnecting channels of tubes are inherently transmission lines. This feature causes interconnections of separate elements to be a serious problem, especially in the case of higher frequencies.

3. Power Recovery

Fluidic devices are inefficient in controlling

fluid power. An average fluidic wall attachment amplifier recovers about 15% of the fluid power supplied to it. Vortex amplifiers may recover as much as 40% of supplied power. Another disadvantage is continual power consumption.

The properties of fluidics and its place among other logic devices were thoroughly evaluated and published in Ref.12 , from where Table 1 and Table 2 were taken.

## The Need of Sensors

Apart from interfacing problems and difficulties with analysis techniques for checking and tuning of fluidic circuits, the absence of sensors is the greatest deficiency in fluidics. Among all other fluidic devices, sensors and their development are covered by the greatest degree of secrecy and most information is clasified. Though the choice of fluidic sensors is not as broad as is the case for electrical sensors, there exists a range of fluidic sensors to detect the quantities of greatest interest, such as mechanical displacement, velocity, level of liquids, flow and pressure. Some of the more frequently used techniques are the methods of pressure sensing, interruptible sensing, vacuum sensing and shock wave or acoustic sensing.

The remainder of this thesis is devoted to the design of a Fluidic Temperature Regulator. The major part of the project deals with the design of the sensing system producing the feedback signal.

| Fluidics Advantage | Electrical Relays | Solid-State Electronics | Integrated Circuits (Electronic) | Conventional Pneumatic Logic | Mechanical Systems |
|---|---|---|---|---|---|
| small size-miniaturization capability | about the same as current technology in fluidics | smaller than current fluidics, potential about same | will always be smaller than fluidics | larger in size, ultimately much larger than fluidics | always larger in size |
| no moving parts | requires moving parts | no moving parts | no moving parts | always has moving parts | always has moving parts |
| not affected by high temperature | would be damaged by high temperatures | would be damaged by high temperatures | would be damaged by high temperatures | could be damaged or rendered inoperative by high temperatures | may or may not be affected by high temperatures, depending upon design |
| not affected by radiation environments | would be damaged by radiation (degradation of insulation materials) | would be damaged by radiation | would be damaged by radiation | would likely be affected by radiation | probably not affected by radiation |
| not affected by high acceleration rates (including shock and vibration) | would be affected by high accelerations | could resist high accelerations if properly supported | would resist high accelerations | would be affected by high acceleration rates | would be affected seriously by high acceleration rates |
| easy to fabricate and produce | fabrication more complex than fluidics | about the same order of complexity as fluidics | about the same or slightly less complex to produce | fabrication process is relatively complex | fabrication process is relatively complex |
| ultimately low cost though not yet achieved | on a production basis, would be higher in cost | probably about the same order of magnitude | less costly | probably more costly than fluidics | probably more costly than fluidics |
| single phase (fluid) systems | requires electrical to mechanical or fluid interfacing | requires electrical to machanical or fluid interfacing | requires multiphase interfacing | single phase (gas) system capability | single phase (mechanical) capability |
| safe for use in hazardous environments | generally not safe for hazardous environments without special precautions | generally would be safe for hazardous environments | would be safe for hazardous environments | may or may not be hazardous, depending upon control means | would not likely be hazardous |

Table 1 Comparison of Fluidics with Other Logic Techniques

| Characteristic | Fluidic Devices | Electrical Relays | Electronics | Hydraulic Devices | Pneumatic Devices |
|---|---|---|---|---|---|
| response | to 1000 Hz (1 ms) | to 200 Hz (5 ms) | to 10 000 000 Hz (1 ms) | to 100 Hz (10 ms) | to 100-150 Hz (10 ms) |
| reliability | excellent (claimed) | generally good, but subject to breakdown | excellent if used within limitations | good, but subject to malfunction | good, but subject to malfunction |
| expected life (cykles) | unlimited | $5x10^5$ - $2x10^6$ cycles generally | unlimited, unless subject to usage beyond rating | $1x10^5$ - $1x10^6$ cycles generally expected | about the same as hydraulics, depends on type |
| contamination tolerance | susceptible to fluid born contamination: solids, oil film, etc. | generally not affected, unless contact resistance would be increased | not affected (moisture and fungus proofing required for severe environments) | susceptible to suspended solids, water, etc. | susceptible to suspended solids, water, etc. |
| resolution | function of number of digits only | function of number of digits only | function of number of digits only | function of number of digits only | function of number of digits only |
| affect of noise | definitely a problem in jet interaction devices; could cause problems in others, can cause device to switch inadvertently | contact bounce can be serious problem, arcing, etc. | less noise than fluidic(signal to noise ratio comparison) | unless noise was of same order of magnitude as signal | unless noise was of same order of magnitude as signal |
| power level (supply) | milliwatts-watt range, generally | types used in logic in fractional to 5 hp range | milliwatt to fractional watt range | to hundreds hp level | to teens hp level |
| volts | — | 24 volts dc 110-220-440 volts ac | 100-3.0volt vacuum tube -28-+28 volt transistor | — | — |
| pressure, psi | 1 inch water, 15 psi | — | — | 5000 psi maximum rated | 125-150 psi maximum rated |

Table 2 Comparison of Performance Characteristics of Fluidics with Other Logic Devices

# CHAPTER 2

# THE FLUIDIC TEMPERATURE REGULATOR

Temperature control has been selected to demonstrate the evolution of a fluidic control system.

Before attempting to design a control system using fluidics, it is well to examine the problem to inspect whether fluidics offers sufficient advantages in terms of performance, reliability, simplicity and/or cost compared to alternative methods. Only seldom would a practical system be built on a purely fluidic basis. Generally, control circuits are required to deliver some output power. Fluidic devices do not operate at sufficiently high power levels to accomplish this. Interfacing is, therefore, required between the fluidic part of the system and the power output device.

It is often desirable to measure and/or control the temperature of some medium under extreme environmental

conditions such as high radiation levels, excessive vibration or corrosive atmosphere. To meet these objectives, an all fluidic system would be the ideal solution.

The feedback portion of the control loop should be designed in such a way that its incorporation into the complete plant will not require major constructional changes in the plant. For example, if it is desired to control the temperature of a liquid flowing in a pipe it should not be necessary to drill into the pipe wall to install a temperature sensor. Furthermore, the actual system design should be governed by considerations of economy and accuracy of performance.

A stock of various fluidic devices manufactured by Corning Glass Works was available for implementation of the system design.

To satisfy constructional requirements the sonic oscillator shown in Fig.2.1 was chosen as a fluidic temperature sensor.

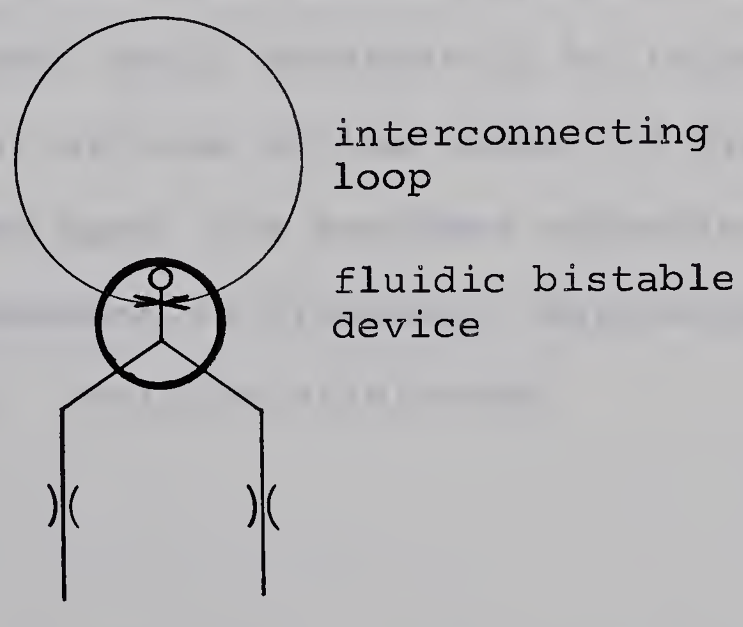


Fig.2.1 A Fluidic Oscillator

The frequency of oscillation of this device is a function of temperature.

The temperature information contained in the variable frequency signal from the oscillator needs to be recovered. Basically there are two choices of method, the digital system and the analog system.

## The Digital System

Most of the fluidic systems reported upon in the literature operated in the digital mode for reasons of convenience and high performance of the available fluidic bistable devices. Since frequency, and not amplitude, is the variable a digital system is readily implemented. However, to measure temperature with an accuracy of say 0.5 degrees centigrade in the range from 0 degrees centigrade to 100 degrees centigrade, one would have to employ a counter capable of distinguishing between two hundred discrete values of frequency. Such a counter would necessarily be rather complicated from the point of view of the number of discrete devices used. On the other hand, the problems connected with such typical analogue phenomena as linearity, saturation and signal to noise ratio would be eliminated.

## The Analogue System

An analogue system of temperature control was chosen as the starting point for the investigation in this

report since an analogue system promises to use fewer components than its digital counterpart. It remains to be demonstrated in this thesis that the analogue system can match the digital system in performance. The design discussed here contains the least number of components for an analogue system.

With the sonic oscillator as a starting point for the design and taking into account the properties of the fluidic devices and of the final actuator, the best solution to the problem of meeting the desired performance goals was found to be a system working in the on-off mode of operation, as shown in Fig.2.2.

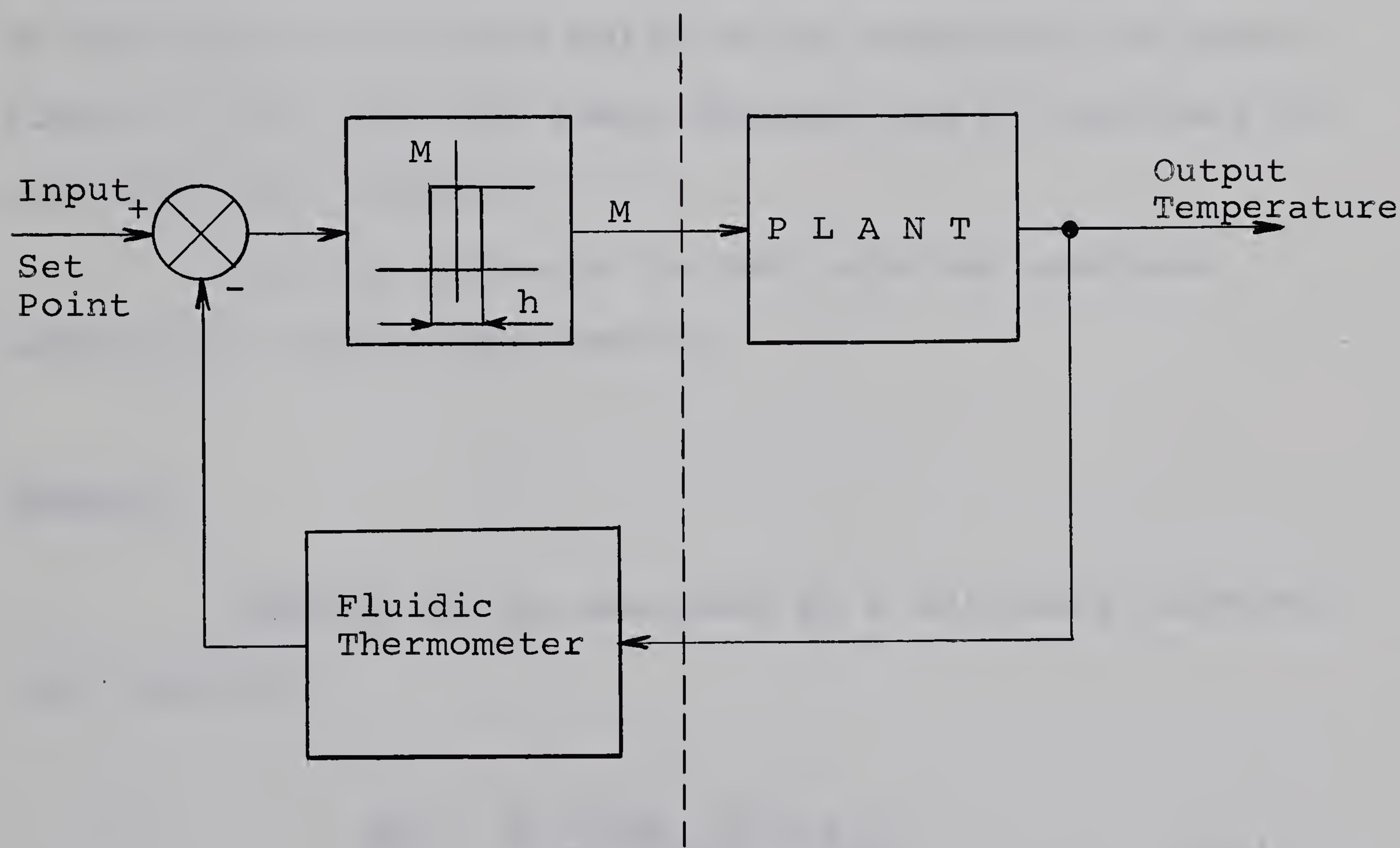


Fig.2.2 Fluidic Temperature Regulator

The plant considered here is a combination of a propane burner operated by a pneumatic switch and a container with water, which is to be kept at a pre-set temperature. The blocks to the left of the dotted line in the block diagram of Fig.2.2 consist of fluidic devices only. Both, the summing point and the nonlinearity are implemented by a single Schmitt trigger. The fluidic thermometer, as shown later, has a time constant that is negligible compared with that of the plant. Therefore, this time constant can be neglected in the following theoretical consideration.

The transfer function of the plant is derived in the following paragraph. It will be assumed that the time constant of the water is dominant and that the time constants of the burner and of the walls of the container are negligible. In this case the plant dynamics can be described by only one time constant.

Let the system be divided into two separate operations, heating and cooling.

Heating

Heating can be described by a following differential equation

$$\frac{dT}{dt} = \frac{Q - 1/R_c (T - T_o)}{m \ c_c} \quad , \qquad (2.1.)$$

where: $T$ = temperature

$Q$ = heat flow

$R_c$ = termal resistance

$m$ = mass

$c$ = specific heat

Let, for convenience, expression (2.1.) be rewritten as

$$dt = \frac{m\ c}{Q - 1/R_c\ (T - T_o)}\ dT \quad . \tag{2.2.}$$

Integration of expression (2.2.) yields

$$t = \int_{T_o}^{T} \frac{m\ c}{Q - 1/R_c\ (x - T_o)}\ dx \quad =$$

$$= mcR_c \quad \ln \frac{1}{Q - 1/R_c\ (x - T_o)} \Bigg|_{T_o}^{T} \quad ,$$

or

$$\frac{t}{mcR_c} = \ln \frac{Q}{Q - 1/R_c\ (T - T_o)} \quad . \tag{2.3.}$$

If the time constant $mcR_c = \tau$ is defined, one can write

$$e^{\frac{t}{\tau}} = \frac{Q}{Q - 1/R_c\,(T - T_o)} \quad . \qquad (2.4.)$$

Solving for the temperature $T$ from expression (2.4.), one can get the final equation describing the heating:

$$T = T_o + QR_c\,(1 - e^{-\frac{t}{\tau}}) \quad . \qquad (2.5.)$$

The product $QR_c$ is a constant and its significance can be derived from expression (2.5.) by letting time go to infinity. Doing this one obtaines:

$$T = T_o + QR_c \qquad (2.6.)$$

which is the final temperature to which the temperature of the water would eventually rise. If the source of heat were sufficiently powerful that the value of this limit exceeds 100 degrees centigrade, the time constant cannot be determined in the usual manner as 63.2 % of the final value. The time can be determined from the initial temperature and from two other points on the curve in Fig.2.3.

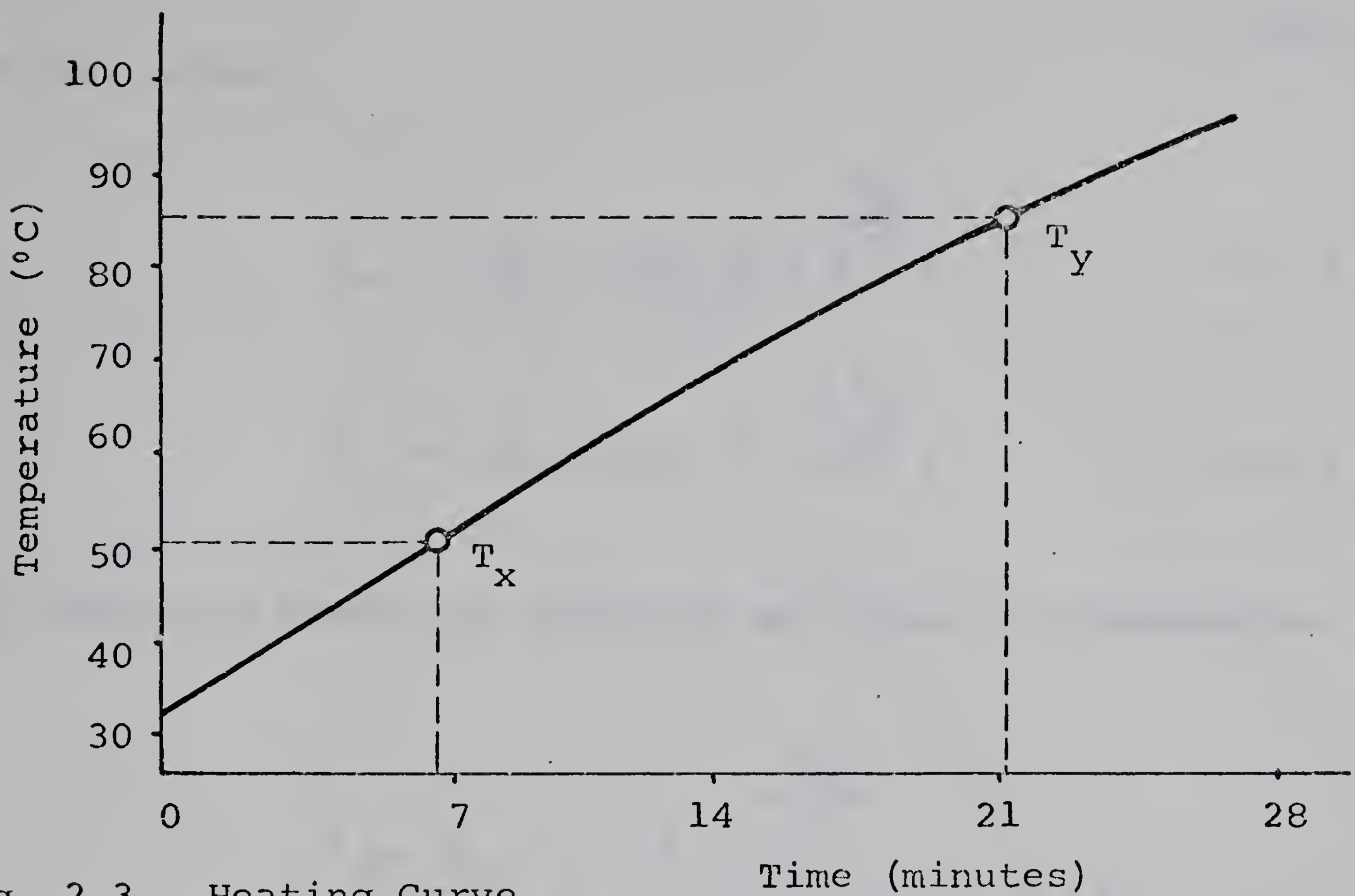


Fig. 2.3 Heating Curve

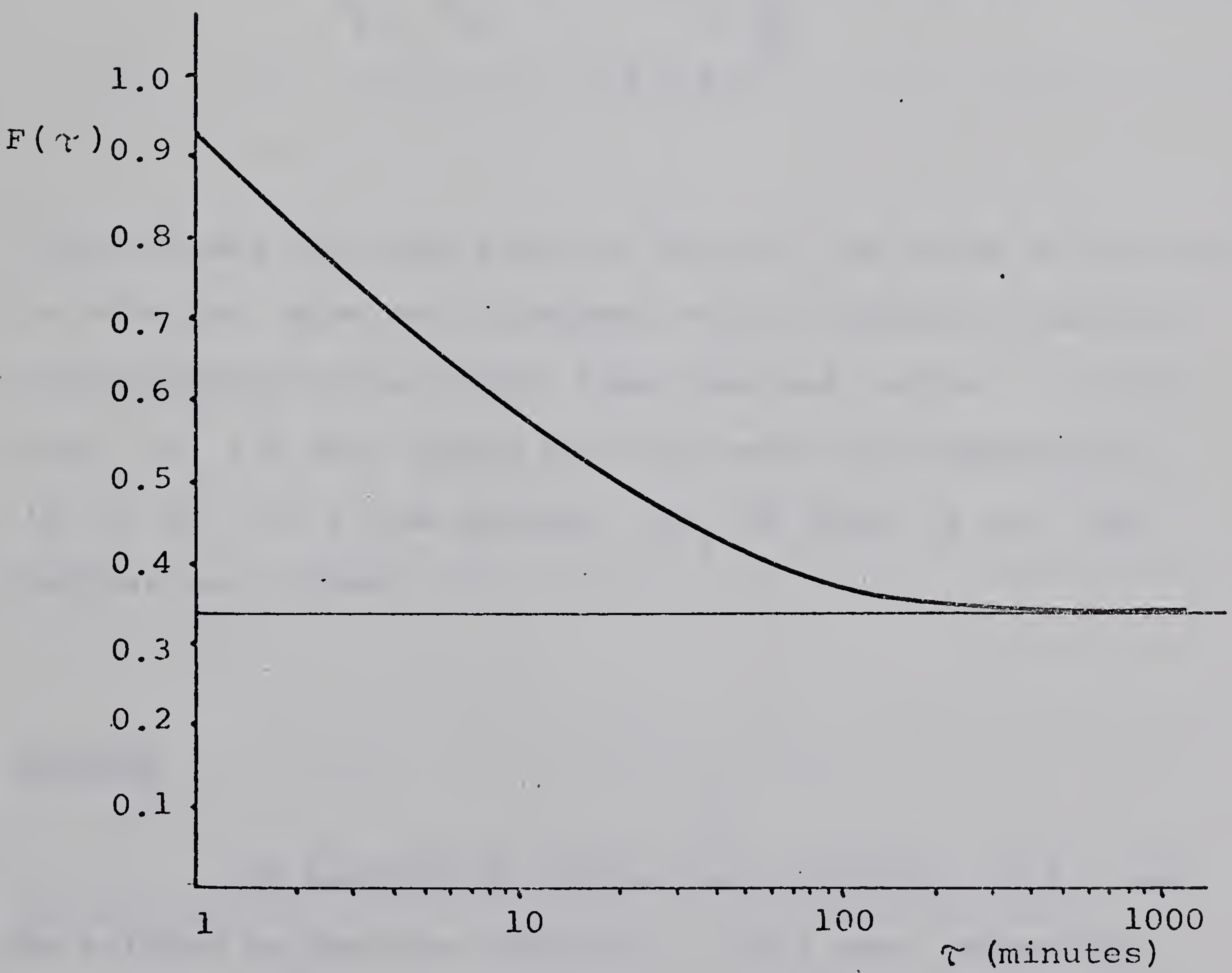


Fig. 2.4 Graph $F(\tau) = (T_x - T_o)/(T_y - T_o)$

We can write:

$$T_x = T_o + QR_c \left(1 - e^{-\frac{t_x}{\tau}}\right) , \qquad (2.7.)$$

$$T_y = T_o + QR_c \left(1 - e^{-\frac{t_y}{\tau}}\right) . \qquad (2.8.)$$

By combining these two equations we obtain the expression

$$\frac{T_x - T_o}{T_y - T_o} = \frac{1 - e^{-\frac{t_x}{\tau}}}{1 - e^{-\frac{t_y}{\tau}}} = F\ (\tau) \ . \qquad (2.9.)$$

Using values from the graph in Fig.2.3 the curve in Fig.2.4. is obtained. From this diagram, we can directly read the corresponding value of the time constant, which, in this case, is 110 min. Inserting this value into expressions (2.7.) or (2.8.) the constant $QR_c$ is found to be 260 degrees centigrade.

Cooling

An expression similar to expression (2.1.) can be written to describe cooling. In this case, since the heating is absent, one can write

$$\frac{dT}{dt} = - \frac{1/R_c \; (T - T_o)}{m \; c} \quad . \tag{2.10.}$$

Rearranging expression (2.10.), one has:

$$dt = - \frac{m \; c}{1/R_c \; (T - T_o)} \; dT \quad . \tag{2.11.}$$

Performing the integration and solving for the temperature $T$ one obtains

$$T = (T_{max} - T_o) \; e^{-\frac{t}{\tau}} + T_o \quad , \tag{2.12.}$$

where $T_{max}$ is the upper theoretical value of the temperature of water.

Here, the time constant can be determined directly from the measured cooling curve, since the final value $T_o$ is known. The time constant thus obtained showed close agreement with that of 110 min. calculated previously.

Using the information obtained from the above calculations, the detailed block diagram of the system can

now be drawn and is shown in Fig.2.5.

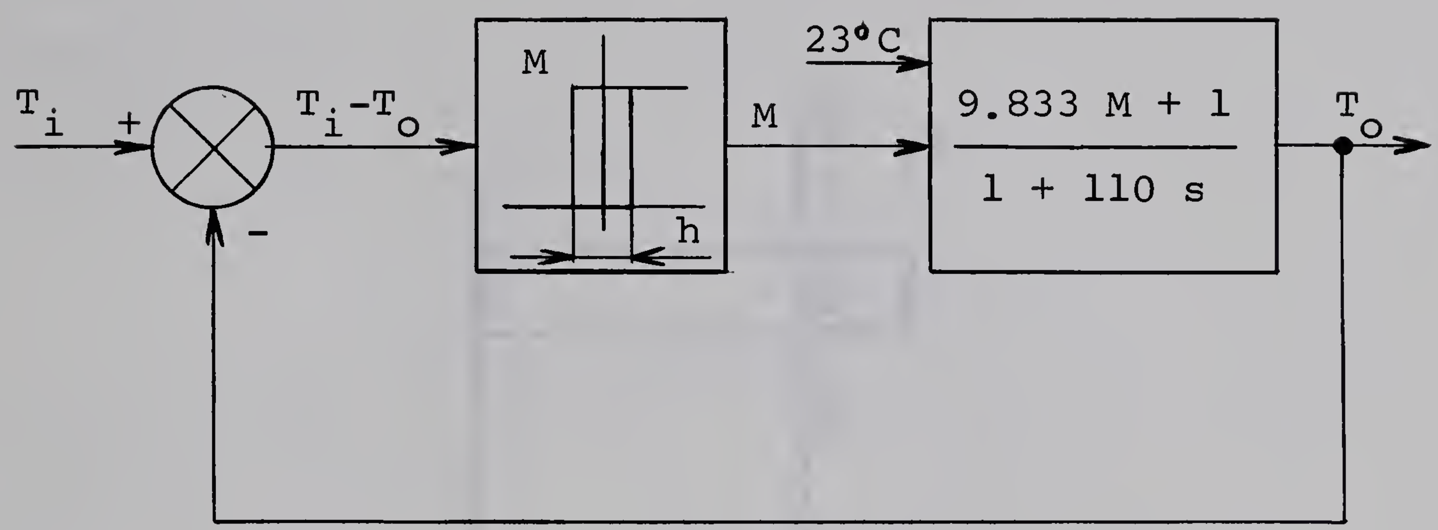


Fig.2.5 Final Block Diagram of the System

The system was simulated on a PDP-8 digital computer. The resulting phase-plane trajectory is shown in Fig.2.6. From this it can be seen that the system has a stable limit cycle with a period of about 8.5 min.

With particular reference to the portion of the system to the left of the dotted line in Fig.2.2 , this is a part implemented exclusively by means of fluidic devices. The fluidic thermometer includes a temperature sensor as well as wave shaping circuits. The Schmitt trigger with its inherent characteristic of a relay with hysteresis serves as a summing and controlling device. In Fig.2.7 a complete block diagram of this part of the system is shown. A detailed discussion of every block is given in the next chapter.

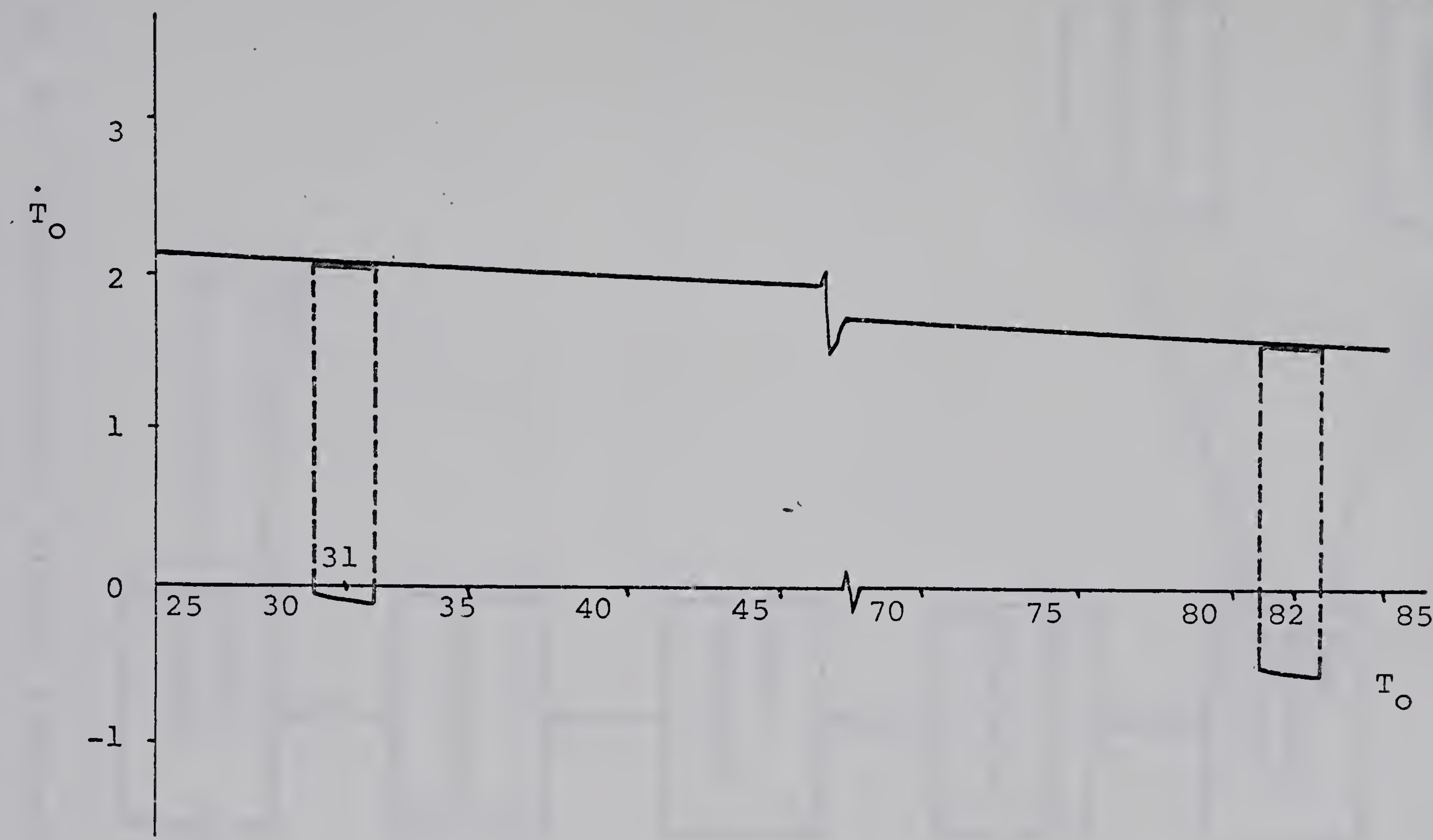


Fig. 2.6 Phase-Plane Trajectory

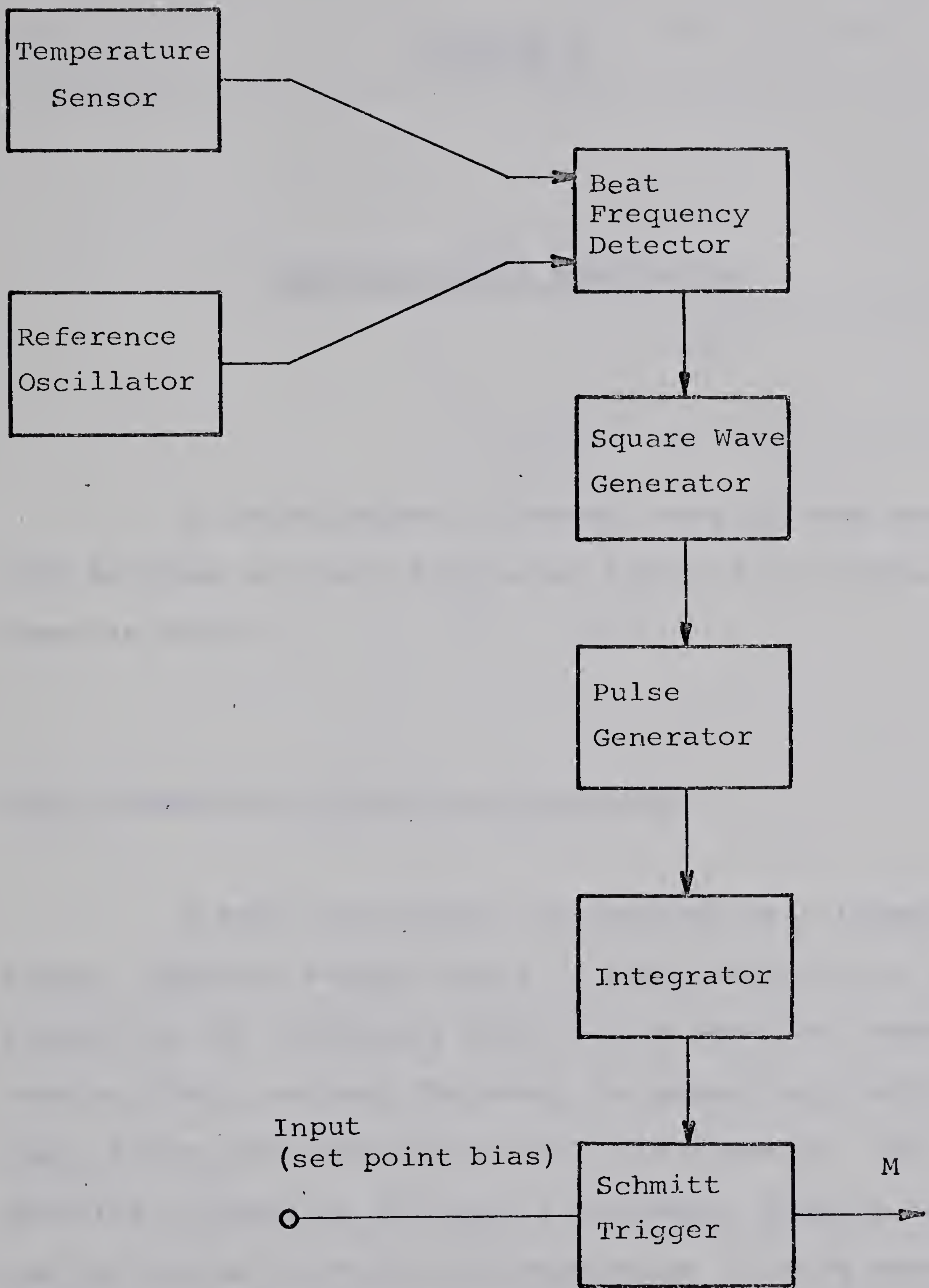


Fig. 2.7 Block Diagram of Fluidic Thermometer

# CHAPTER 3

## FUNCTION BLOCKS DESCRIPTION

In this chapter a thorough step by step description is given of every functional block of the system as shown in Fig.2.7.

### Sonic Temperature Sensitive Oscillator

A sonic oscillator was employed as a temperature sensor. There are several types of sonic oscillators described in the literature which can be used for temperature sensing. Their natural frequency is temperature sensitive. Some of them are considered highly confidential and no detailed information on them is available. Some of them use the medium of which the temperature is to be measured as their working fluid and are, therefore, useless for this project. A new type of an oscillator had to be developed for this project which combined the useful properties and eliminated the drawbacks of oscillators known so far.

The operation of the oscillator utilizes the sonic delay time in a feedback loop of a bistable amplifier to generate the frequency signal. Schematically the oscillator, producing sine waveforms at its output, is shown in Fig.3.1.

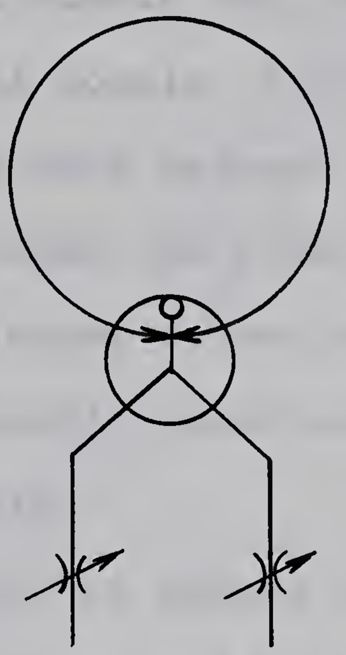


Fig.3.1 Sonic Oscillator

The active element of the oscillator is a non-vented, symmetric, bistable amplifier. The amplifier switches states when the flow from either of its outputs is temporarily restricted. The control ports are interconnected by a feedback loop.

The oscillator operates as follows. When the supply air is introduced to the supply port, a jet is formed in the power jet chamber. The stream of air attaches itself to either of the walls and the output appears at the corresponding output port. Suppose that the jet has attached

itself to the right wall. At the same instant an expansion wave begins to propagate away from the right control nozzle and travels along the interconnecting loop between the control nozzles. Simultaneously, a compression wave propagates from the left control port. As soon as the expansion wave reaches the left control nozzle and the compression wave reaches the right control nozzle, a switching of states occurs . The switching occurs because at the instant that the compression wave reaches the right control nozzle the pressure conditions no longer favour the Coanda effect. Furthermore, these favourable conditions are re-established at the left control nozzle.

For oscillations to appear the bistable amplifier must be properly loaded. The load will establish the necessary pressure conditions inside the power jet chamber.

The frequency of oscillations is primarilly determined by the time the sonic wave needs to travel from one control nozzle to the other, or alternately by the length of the interconnecting feedback loop where the length of the channels inside the bistable amplifier should be taken into account. The frequency is,furthermore, affected by the time required for switching. The switching time depends upon the pressure inside the jet power chamber, or, on the load connected to the outputs. The switching time depends also upon the attenuation experienced by the waves while traveling along the interconnecting channel. The effect of the load upon frequency is shown in the diagram in Fig.3.2.

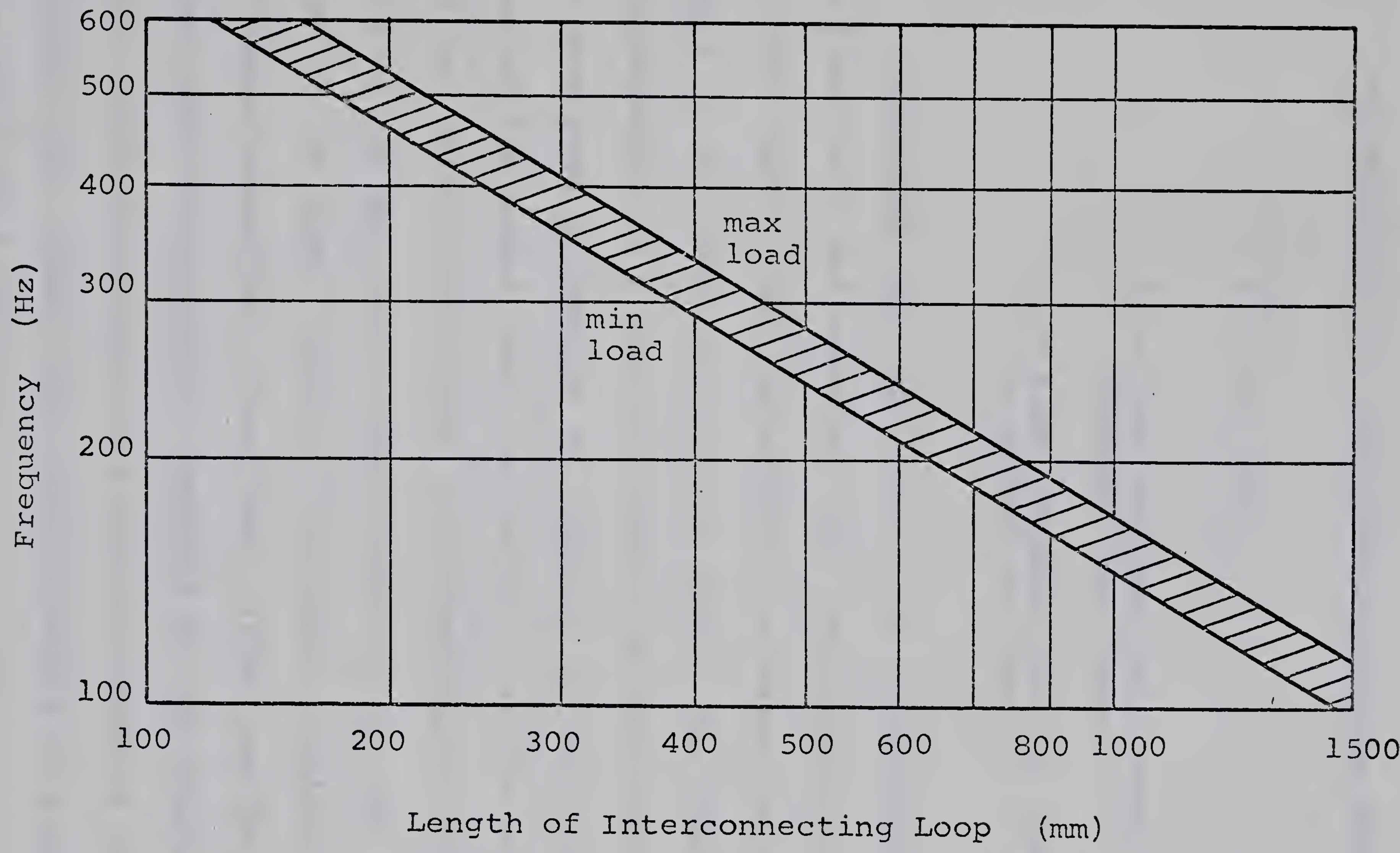


Fig. 3.2 Effect of Load upon Frequency of Sonic Oscillator

The shaded part of the diagram illustrates the range where the oscillations for the particular length of the inter-connecting channel occur.

The period of the oscillations can be described by:

$$T = 2t_c + 2t_s , \qquad (3.1.)$$

where:

$t_c$ = time required for a wave to traverse the channel ,

$t_s$ = time required for the impact wave to switch the jet.

Assumming that the flow in the interconnecting loop is isentropic and assuming that the amplitude of the wave is very small, then the velocity at which the wave propagates is the local velocity of sound. The speed of sound propagating in a gas contained in a tube generally depends upon such properties as diameter of the tube, frequency of the sound, heat conductivity of the material of the tube, velocity of sound in the material of the tube, viscosity of the gas, heat conductivity of the gas and character of the inner surface of the tube. Neglecting some of these properties, since their effect on the ve - locity of sound is negligible compared to the others, and expressing the properties of the tube in terms of fluidic transmission line theory, the local velocity of sound can be expressed as (Ref.14.)

$$v = c \left(1 + R_1^2 / \omega^2 L_1^2 \right)^{-\frac{1}{4}} \qquad (3.2.)$$

where: $c$ = velocity of sound in the unbound atmosphere,

$R_1 = 8\mu / \pi r^4$ , resistance per unit length,

$L_1 = \rho / \pi r^2$ , inductance per unit length.

In our case, the tube is a copper pipe with air inside, thus we have:

$r = 1/8''$ ,

$\mu = 1.01 \times 10^{-6}$ lb/in sec ,

$\rho = 4.7 \times 10^{-5}$ lb/ in$^3$

and we get the following values for the lumped parameters:

$R_1 = 0.1673$ RU , $L_1 = 3.83 \times 10^{-3}$ IU .

The angular frequency for which $R_1 / \omega L_1 = 1$ is,

$\omega = 43.4$ rad/sec, which corresponds to a frequency of 6.95 Hz. For this frequency

$v = 0.84\ c$ .

In the case of the fluidic oscillator, the frequency is expected to be much higher so that $R_1 < \omega L_1$ and therefore the local velocity of sound is only slightly less than the velocity of sound in the unbound atmosphere.

The time $t_c$ required for the wave to traverse the loop is given by $t_c = d / v$ , where $d$ is the length of the interconnecting loop.

Expression (3.1.) can be rewritten as

$$T = \frac{2d}{v} + 2t_s \quad . \qquad (3.3)$$

The frequency of the oscillator is then the inverse of T.

The frequency of the oscillator depends on temperature. In our case, air is used as the working fluid; therefore, the frequency is affected by the temperature dependency of the velocity of sound in air.

The velocity of sound in air depends on temperature according to the formula

$$c = 331.45 \quad (T / 273)^{\frac{1}{2}} \quad (m/sec), \qquad (3.4)$$

or

$$c = K \quad T^{\frac{1}{2}} \quad . \qquad (3.5.)$$

Hence the speed of sound increases by about 0.6 m/sec. per degree centigrade.

From the above considerations the sensitivity of the oscillator to temperature can be derived. From expression (3.3.) the frequency of the oscillator can be expressed as 1 / T. The sensitivity is then the derivative of frequency with respect to temperature.

$$\frac{df}{dT} = \frac{K}{4T^{\frac{1}{2}} d} \quad . \qquad (3.6.)$$

Measurements of temperature sensitivity were performed and the results are shown in Fig.3.6.

The actual temperature sensor as it was built is shown in Fig.3.3.

The bistable amplifier used is a device manufactured by Corning Glass Works type FD 2211-2-1211. The vents were blocked. The control ports were connected by a copper pipe of inside diameter 3.2 mm ($\doteq$ 1 / 8 "). Two valves were connected to the output ports to serve as an adjustable load. This configuration proved to be very succesful. The copper pipe can be either submerged into the medium of which the temperature is to be sensed, or it can be wound around and soldered to the pipe through which the medium flows. Two oscillators of the same configuration are being employed in this project.

The following characteristics of the temperature sensor were measured:

1. dependency of frequency upon the length of the interconnecting loop, Fig.3.4.,

2. dependency of frequency upon the supply pressure, Fig.3.5. ,

3. dependency of frequency upon temperature, Fig.3.6.,

4. dependency of the difference in oscillator frequency between that at 0 degrees centigrade and that at 100 degrees centigrade determined as a function of basic frequency at 0 degrees centigrade.

Fig. 3.3 Temperature Sensor

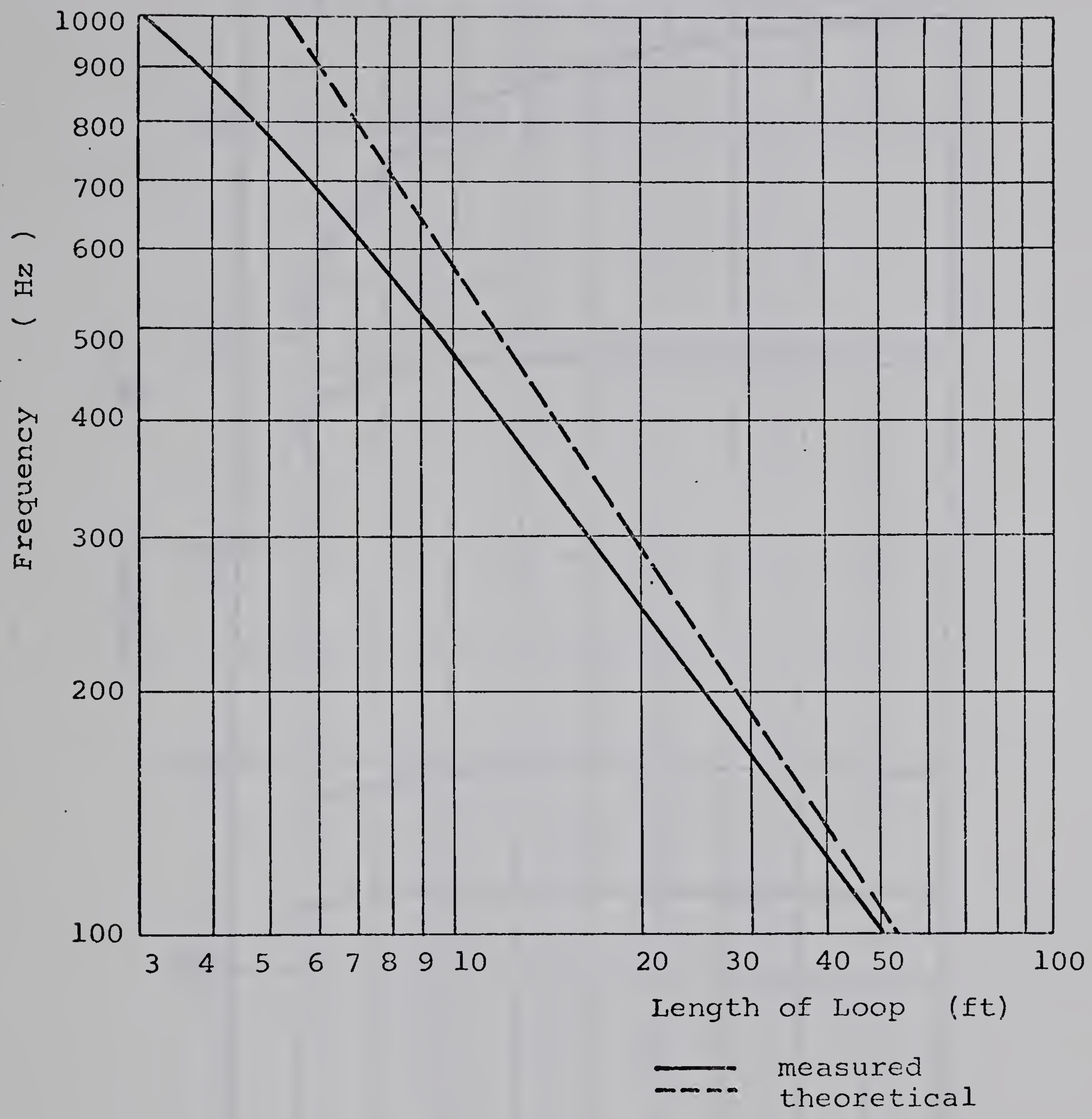


Fig. 3.4 Dependency of Frequency upon Length of Interconnecting Loop

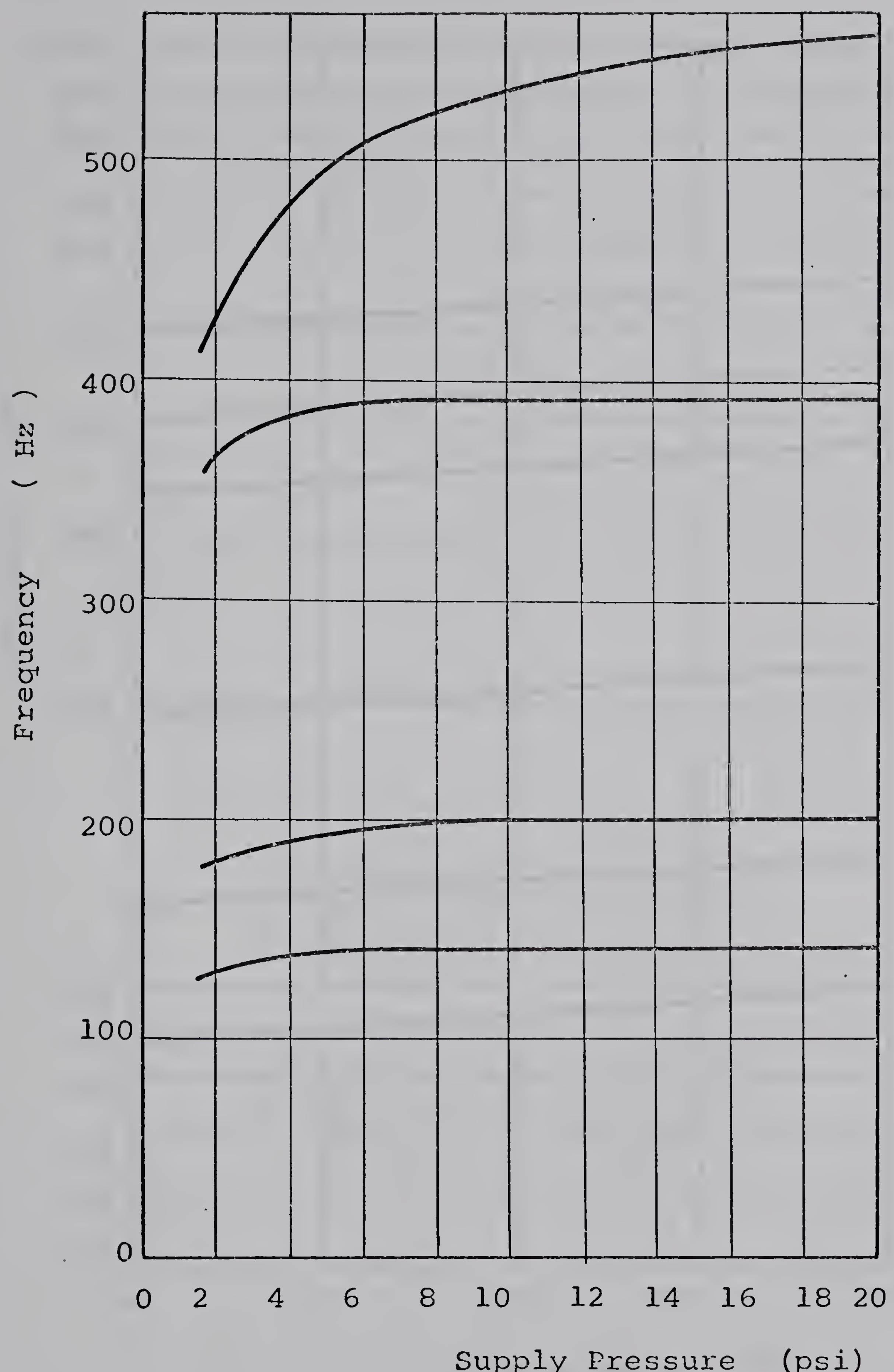


Fig. 3.5 Dependency of Frequency upon Supply Pressure

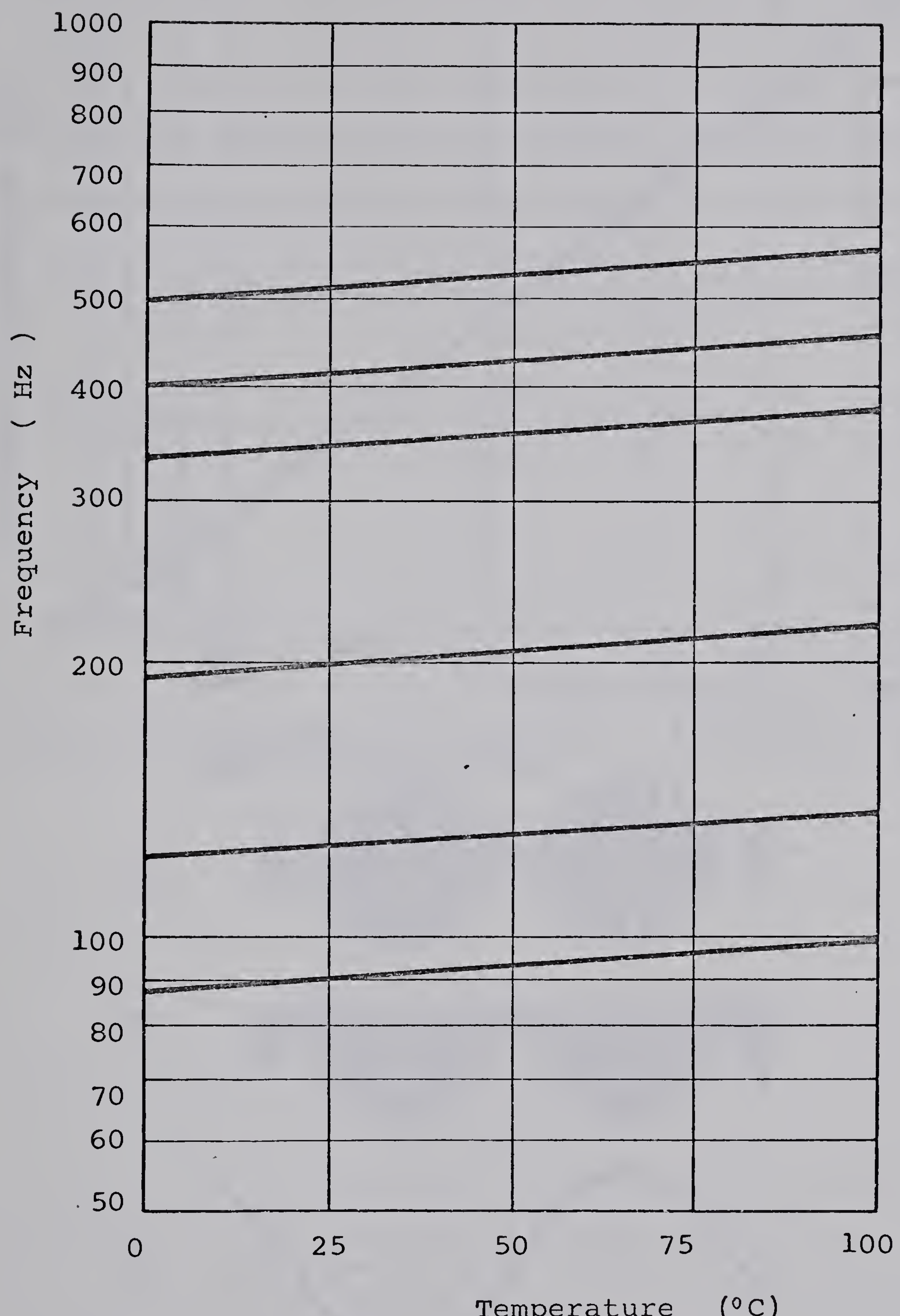


Fig. 3.6 Dependency of Frequency upon Temperature

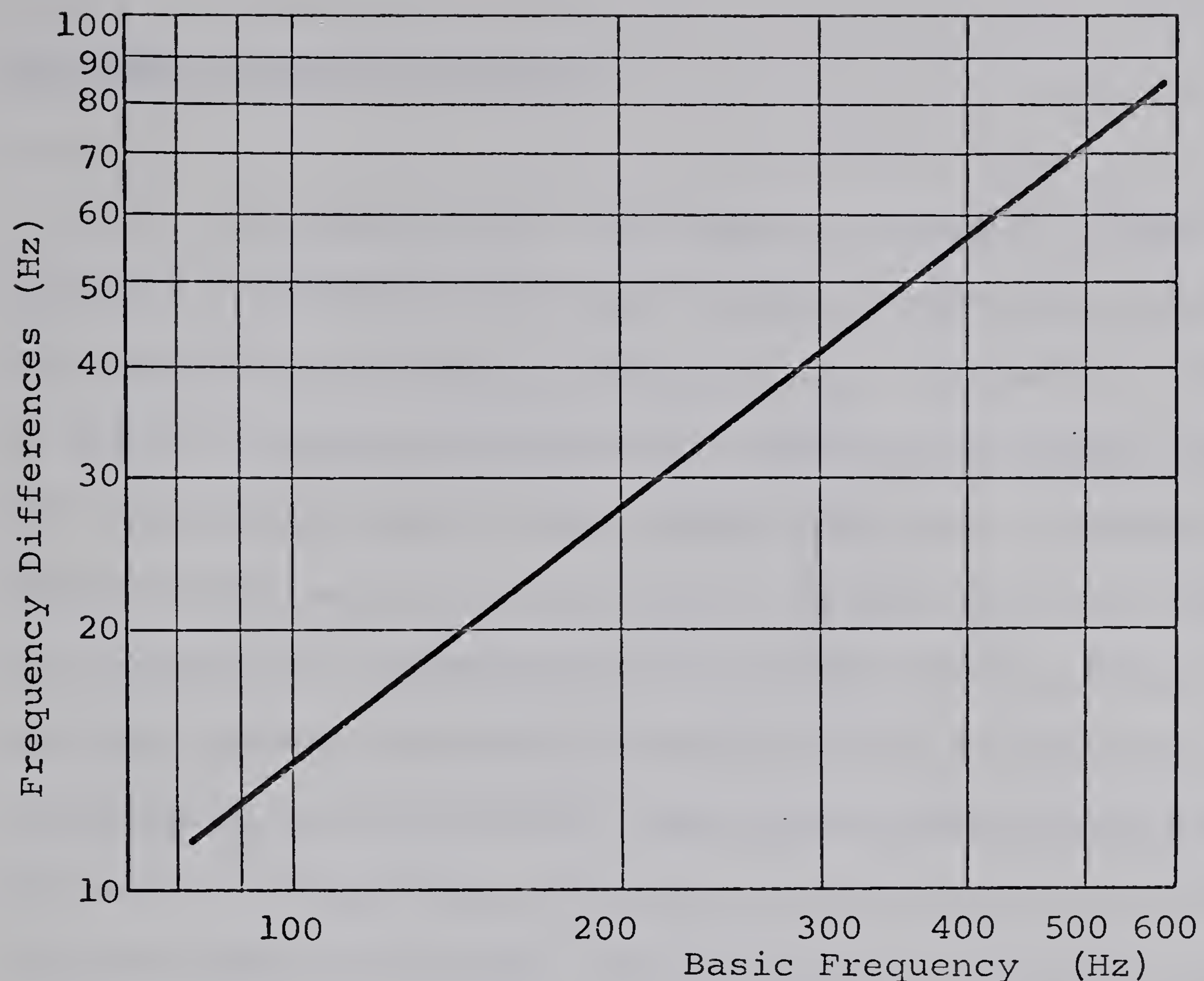


Fig. 3.7 Dependency of Frequency Differences (over 100 °C) upon Basic Frequency

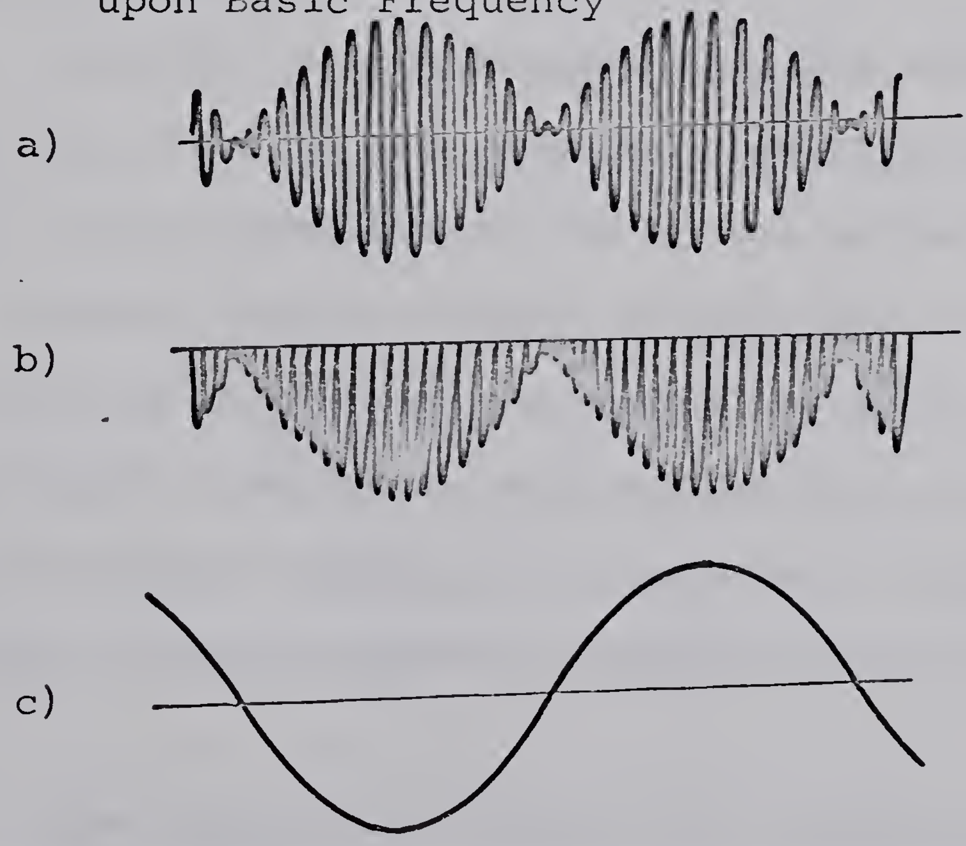


Fig.3.8 Beat Frequency Generation

The Beat Frequency Detector

It can be seen from Fig.3.6 or Fig.3.7 that to obtain a reasonable sensitivity and satisfactory accuracy of the system, the basic frequency (the frequency at 0 degrees centigrade) should be chosen sufficiently high. Let us suppose that we have chosen the basic frequency at 500 Hz. This means that the entire system should be capable of operating to frequencies of at least 600 Hz. Even if devices capable of working satisfactorily at such high frequencies were available, the overall performance would be highly uneconomical. From the entire bandwidth of 600 Hz only the portion between 500 Hz and 600 Hz would be used for actual temperature sensing.

The data on the highest possible frequencies at which fluidic devices are capable of working differ, depending on the manufacturer and on the actual application. In this project where standard Corning Glass Works devices were used, and particularly in those instances where digital fluidic components such as bistable amplifiers,NOR gates and Schmitt triggers were employed, the maximum frequency for reliable operation appeared to be 50 pulses per sec.

The temperature sensitivity of the oscillator frequency is a function of its frequency at 0 degrees centigrade; in fact, this sensitivity increases with

increasing operating frequency. It is, therefore, desirable to make the oscillator frequency as large as possible. However, as indicated above, the maximum frequency of operation of the components following the sensor is 50 Hz. The need for high sensitivity and limited bandwidth dictate the use of a beat frequency technique.

At this stage consider the beat frequency detector as a device which at its output produces the difference between the two input frequencies. There are two methods of obtaining a beat frequency proportional to temperature. The first method requires two oscillators, each heated, but of two slightly different and relatively high basic frequencies, i.e. in the range between 4 kHz and 5 kHz. The graphs of Fig.3.6 and Fig.3.7 give an indication of this mode of operation. The sensitivity of the higher frequency oscillator is greater than that of the lower frequency one. The resulting difference in sensitivities is proportional to temperature.

In our case, when using the sonic oscillator as shown in Fig.3.1 , the operating frequencies are about 400 Hz rather than 4 kHz and another technique, not as flexible as the first one, must be used. Again, there are two oscillators of which the basic frequencies are set to obtain the required difference frequency, but one of them serves as a reference oscillator. The reference oscillator delivers a constant frequency signal to the input of the beat detector which implies that this oscillator should be

kept at a constant temperature. Using the graph in Fig.3.7 , and keeping in mind that the beat frequency should not exceed 50 Hz both the temperature sensor as well as the reference oscillator are designed. The upper and lower difference frequency values were chosen as 50 Hz and 7 Hz, which corresponds to a change of 43 Hz. Using the above values and Fig.3.7 , the sensor oscillator frequency is found as 330 Hz at 0 degrees centigrade. The reference oscillator frequency should thus be 7 Hz lower or 323 Hz.

An attempt was made to use these low frequency oscillators to produce a beat frequency signal in the same manner as that suggested for the higher frequency oscillators (i.e. at 4 to 5 kHz) - without the need of a reference. The resolution attained by this method was not high enough to secure the required accuracy. It can be seen from the graph in Fig. 3.7. Suppose the basic frequencies are chosen 400 Hz and 440 Hz respectively. Then the difference in temperature sensitivities produces a difference frequency at 0 degrees centigrade of approximately 5 Hz, which is less than 12% of the resolution achieved using the fixed reference oscillator.

Concentrating our attention on the process of obtaining the beat frequency signal itself and on recovering of the information contained therein , the following operations must be carried out:

1. The two input signals must be mixed to derive the signal shown in Fig. 3.8a ( the desired beat fre-

quency signal corresponds to the main signal envelope, or, in other words, it is the frequency of changing of the amplitude).

2. This signal must be detected in order to recover the beat frequency signal. After detection the signal, as shown in Fig. 3.8b, is obtained which contains frequencies equal to the difference as well as to the sum of the two carrier frequencies, while the signal shown in Fig. 3.8a contains only the two carrier frequencies.

3. The sum frequency must be filtered out in order to recover the desirable difference or beat frequency. It was accomplished by means of low - pass filters; the resulting signal is shown in Fig. 3.8c.

The practical realization of the beat frequency detector is shown in Fig. 3.9.

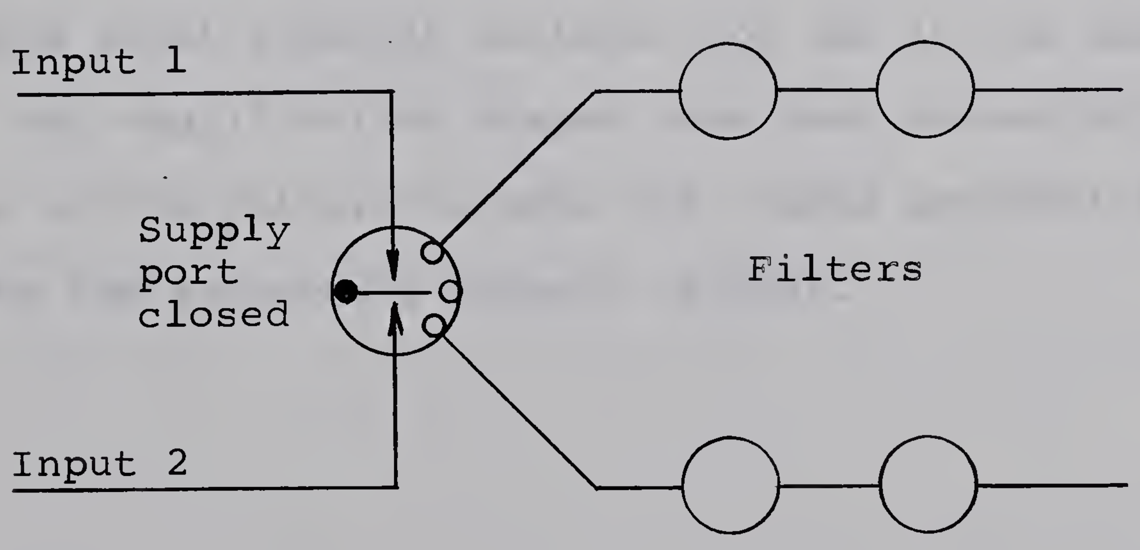


Fig. 3.9 Beat Frequency Detector.

The Corning Glass Works centre - dump jet interaction amplifier was found to be the most suitable device to perform the beat frequency detection. The amplifier is operated in a passive mode with the supply pressure port blocked off. The input signals are connected to their respective input ports into the amplifier. The amplitudes of the two input signals are adjusted so that mixing and detecting are accomplished simultaneously by this single device. The centre - dump jet interaction amplifier as used here has an additional advantageous feature. The centre dump causes the d-c level and/or its changes to be minimal. This is very imporant with respect to the succeeding stage, the square wave generator. Low-pass filters are connected to each output port of the amplifier. The low-pass filters consist of two fluidic capacitors (3.75 $cm^3$) connected by a pipe of 32 cm length. This configuration proved to be succesful and filtering out of the sum frequency was sufficiently efficient. Since the beat frequency detector as built is a passive device, its output signal level was below the level directly suitable for use in the subsequent stage. Two amplification stages have been connected to the outputs of the filters to make the signal powerful enough to drive the succeeding Schmitt trigger.

Design of the Amplifier

1) Static Matching

The main goal of the static matching design is the calculation of supply pressures to set the operating points of each stage. As the first stage, a centre- dump amplifier was chosen because it remains stable under all loading conditions. For the succeeding stage an amplifier without centre dump was chosen because of its higher gain. On the other hand, it must be sufficiently loaded not to become unstable. The input impedance of a Schmitt trigger proved to fall within a load range for which the operating point of an amplifier is in the stable region. The supply pressures were calculated using the input and output characteristic of Appendix A as follows:

1) The beat signal was measured using an anemometer. From this measurement and using the input characteristics of a centre dump amplifier, the flow signal was transformed into the pressure signal, since the characteristics of fluidic amplifiers are usually expressed in terms of pressures, and its maximum value was determined to be $P_{c1} = 0.06$ psi.

2) Using the nondimensionalized output characteristics of the centre-dump amplifier and choosing $P_{cd}/P_s = 0.04$

as an optimal value, the supply pressure of the first stage was determined to be $P_{s1}$ = 1.5 psi.

3) Choosing the proper curve corresponding to $P_s$ = 1.5psi from the output characteristics of the centre-dump amplifier and superimposing the input characteristic of the non-centre-dump amplifier, the input pressure to the second stage was found to be $P_{c2}$ = 0.16 psi.

4) Using the procedure of step 2), the supply pressure of the second stage was calculated as $P_{s2}$ = 4.0 psi.

The actual pressures as they were measured on the optimally adjusted amplifier, were $P_{s1}$ = 1.4 psi and $P_{s2}$ = 5.7 psi. The output of the amplifier was then $P_o$ = 1.2 psi. This result was obtained with the amplifier loaded with the input impedance of the following Schmitt trigger. The Schmitt trigger input signal is thus in a range for reliable operation.

2) Dynamic Performance

Since the amplifier is working in the intermediate range of frequencies [1], small signal analysis should be employed to determine its dynamic behaviour. The equivalent circuit, as derived by Belsterling and Tsui [5], is shown in Fig. 3.10. Two such stages are cascaded in this case with the second one loaded by the input circuit of the Schmitt

trigger.

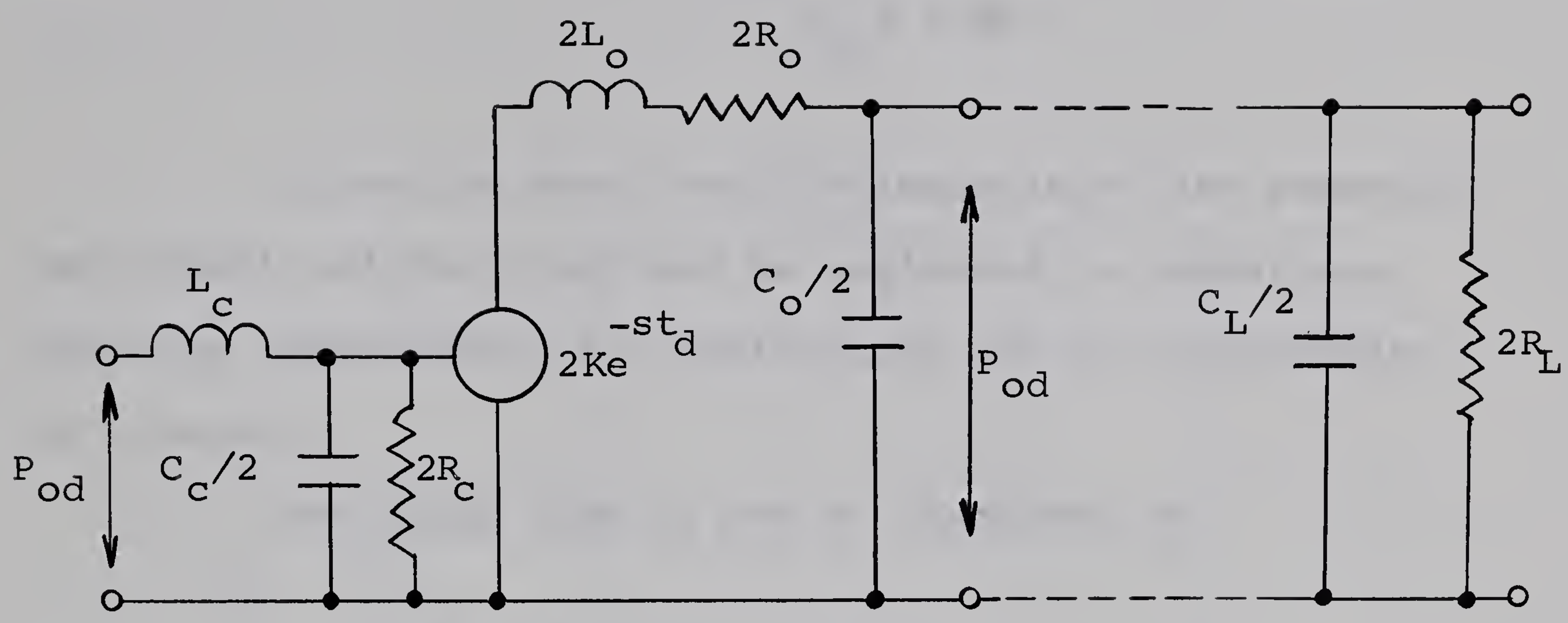


Fig. 3.10 Equivalent Circuit of the Fluidic Amplifier

The circuit element values were obtained from the measured characteristics and from geometrical dimensions of amplifiers and from the physical properties of the working air. The calculated values were:

| | |
|---|---|
| $L_{c1} = 2.5 \times 10^{-5}$ IU | $L_{c2} = 3.2 \times 10^{-5}$ IU |
| $C_{c1} = 0.22 \times 10^{-2}$ CU | $C_{c2} = 2.38 \times 10^{-3}$ CU |
| $R_{c1} = 3.02$ RU | $R_{c2} = 1.0$ RU |
| $K_1 = 2.7$ | $K_2 = 7.5$ |
| $L_{o1} = 3.2 \times 10^{-5}$ IU | $L_{o2} = 5.5 \times 10^{-5}$ IU |
| $R_{o1} = 0.18$ RU | $R_{o2} = 0.67$ RU |

$$C_L = 3.75 \times 10^{-3} \text{ CU}$$

$$R_L = 1 \text{ RU}$$

It can be seen that the inductances are generally very small and that they can be neglected in comparison with the capacitances and resistances for the frequencies of interest.

The delay time $t_d$ can be expressed as

$$t_d = t_1 + t_2 + t_3 + t_4 \; ,$$

where:

$$t_1 = \frac{\text{length of control port}}{\text{velocity of sound in the moving fluid + velocity of the fluid}} \; ,$$

$$t_2 = \frac{\text{length of interconnecting chamber}}{\text{velocity of fluid flow}} \; ,$$

$$t_3 = \frac{\text{length of output port}}{\text{velocity of sound in the moving fluid + velocity of the fluid}} \; ,$$

$$t_4 = \frac{\text{length of output duct}}{\text{velocity of sound}} \; .$$

The value of $t_d$ is usually in the order of 0.5 millisec which is approximately one order of magnitude

smaller than the actual RC time constants. Under these assumptions, the original equivalent circuit can be simplified as shown in Fig. 3.11.

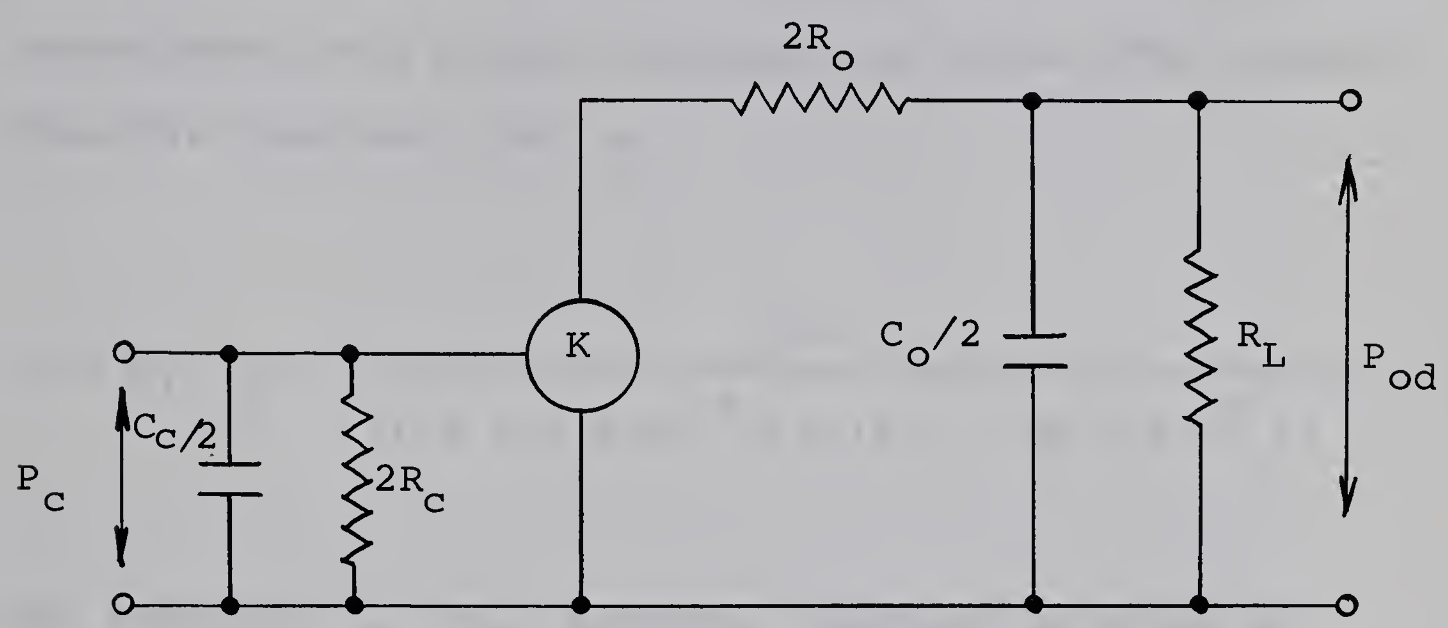


Fig. 3.11 Simplified Equivalent Circuit

The transfer function of this circuit is

$$G(s) = \frac{M}{1 + \dfrac{s\, C_o\, R_o\, R_L}{R_o + R_L}} ,$$

where:

$$M = \frac{K\, R_L}{R_o + R_L} .$$

Inserting the known values, one gets M=4.5,

while the time constant for the second stage becomes 1.5 millisec , which corresponds to a corner frequency of 106 Hz. In the case of the first stage one arrives at $M = 2.37$ with a time constant of 3.64 millisec , which corresponds to a corner frequency of 44 Hz. The overall transfer function then is

$$G = G_1 \, G_2 = \frac{10.7}{(1 + 1.5 \times 10^{-3} \, s) \, (1 + 3.34 \times 10^{-3} \, s)} \, .$$

The Bode plot of this transfer function is shown in Fig. 3.12. The bandwidth is 48 Hz, which is satisfactory for this case.

## Square Wave Generator

A Corning Glass Works Schmitt trigger was employed as a square wave generator. The principle of operation of a square wave generator is as follows. If a sinusoidal beat frequency signal is introduced into one input of the trigger and a d-c bias signal into the other, then two complementary square wave signals as shown in Fig. 3.13 will appear at the outputs of the Schmitt trigger.

Only one output, as shown in Fig. 3.13 , has

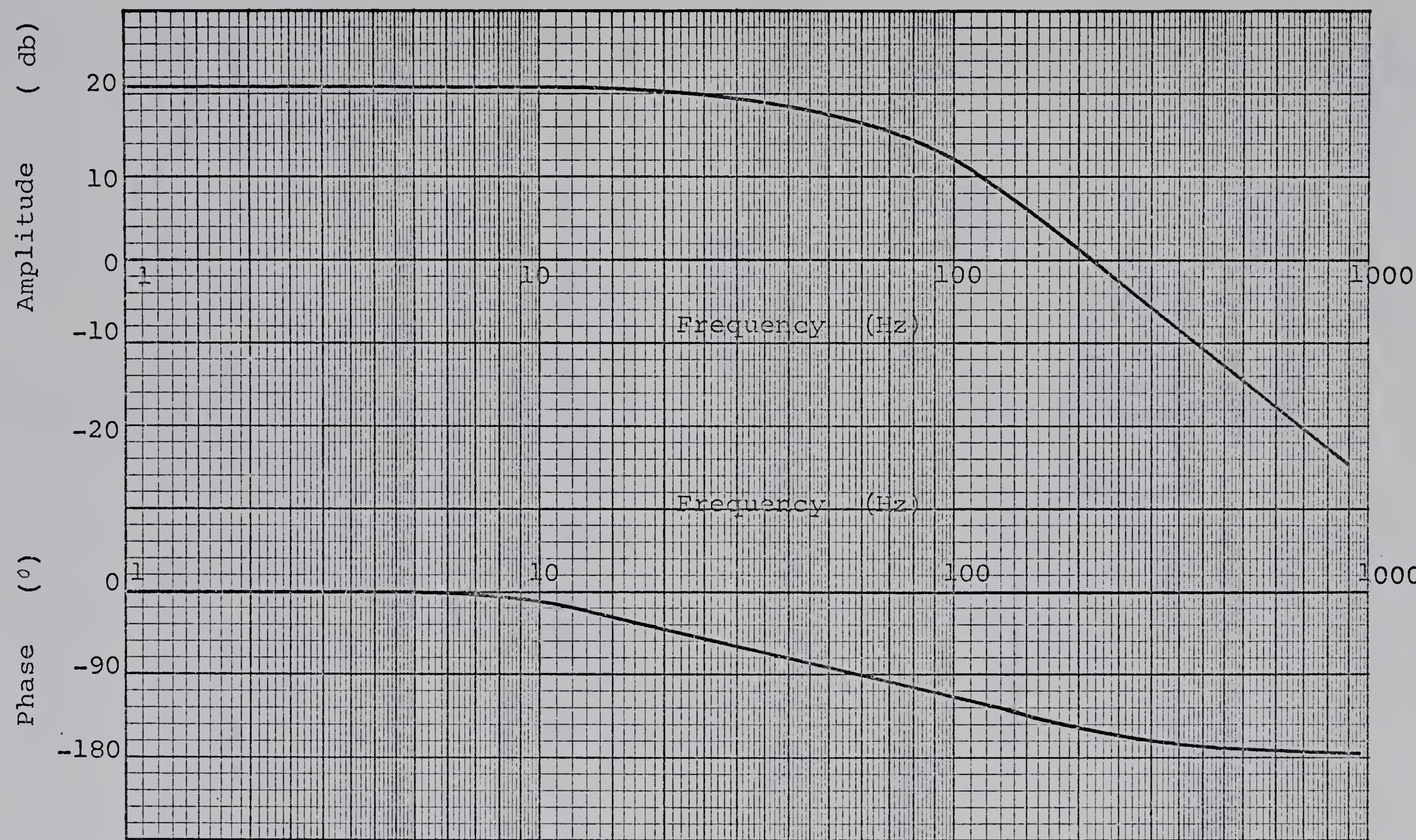


Fig. 3.12 Bode Diagram of Amplifier

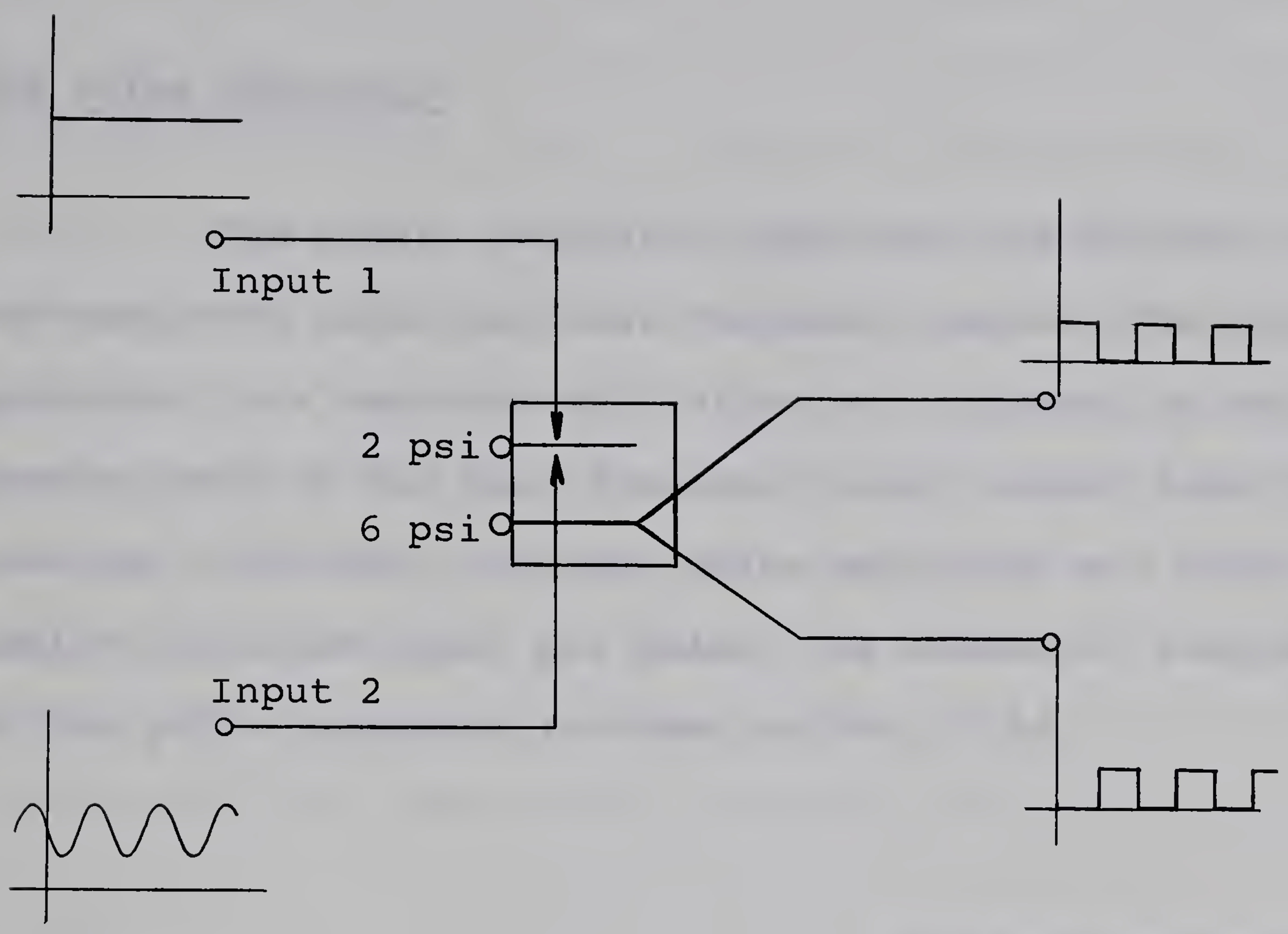


Fig. 3.13 Principle of Operation of the Square Wave Generator

been utilized to drive the pulse generator which follows. To drive the pulse generator efficiently one stage of amplification was found necessary. Since all temperature information is contained in the repetition rate a flip-flop can be used, in this case, to increase the signal amplitude. The amplitude of the input pulses to the flip-flop is 1.6 psi. Thus, using Fig. 3.16 the required flip-flop supply for accurate switching can be calculated. The appropriate supply pressure was found to be 12 psi.

<u>The Pulse Generator</u>

The pulse generator generates one constant width and amplitude pulse per beat frequency period. The pulse generator is a one-shot multivibrator triggered by each leading edge of the beat frequency input signal from the previous flip-flop. Constant pulse amplitude and width implies constant power per pulse. The schematic diagram of the pulse generator is shown in Fig. 3.14.

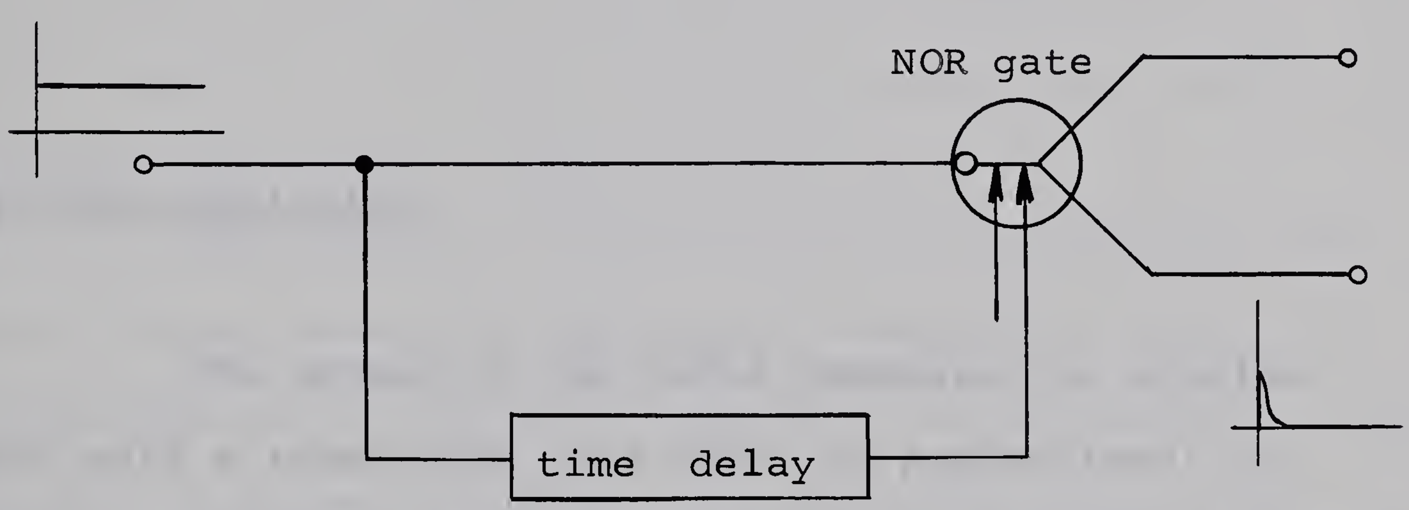


Fig. 3.14 Pulse Generator

The device employed is a Corning Glass Works NOR gate operated in a passive mode. The circuit operates as follows. The input pressure step is split into two streams. One leads directly to the supply pressure port of the NOR

device and causes output pressure to appear at its NOR output. The other stream travels along an auxiliary loop, which provides time delay. Hence, a step of pressure delayed with respect to the pressure step at the supply port of the device appears at its input and causes the output (at the NOR output) to switch to the OR output. As a result, a pulse is generated at the NOR output. The width of this pulse depends on the time delay of the auxiliary loop. The delay in the loop depends on the flow restriction in the loop and therefore the width of the output pulse can be varied by adjusting the restrictor interconnected in the loop.

## The Pulse Amplifier

The output of the pulse generator is a pulse train with a repetition rate which is proportional to sensed temperature. This pulse train can be readily integrated and the d-c pressure level of the integrator, again proportional to the sensed temperature, can be functionally used as a feedback signal. But, the integrator is a passive RC network having attenuation and its output level would be too low to succesfully perform the required operations. There are two methods of obtaining the d-c output pressure signal of a useful amplitude. First, the d-c output from the integrator can be amplified by an analog amplifier. Such an amplifier would consist of several stages

of beam deflection fluid amplifiers. The second method chosen for this project is to amplify the pulses before they are fed into the integrator. The pulse amplifier would consist of several stages of fluidic wall attachment amplifiers. By the latter method the problems of analog amplification such as nonlinearity and saturation would be avoided.

The final design of the power pulse amplifier is shown in Fig. 3.15. The pulses from the output of the pulse generator are fed into the NOR gate which is the first stage of the power amplifier. The NOR gate provides two complementary pulse trains at its outputs. These two output pulse trains drive differentially the second stage, a bistable amplifier. All the following stages also consist of differentially driven bistable amplifiers.

The objective of the design is to determine the supply pressures of each amplifier. The total number of stages required in the power amplifier is determined by the NOR gate output amplitude of 0.7 psi and by the final supply pressure of 26 psi.

The matching and staging of bistable amplifiers was done by calculating graphically the supply pressures using the input and output characteristics. The graph in Fig. 3.16 proved to be very useful for the design. The upper curve represents the recovery of the bistable devices. The lower curve was obtained from the input characteristics. The latter shows the conditions for the switchings to occur. Using this graph the supply pressures as well as the number

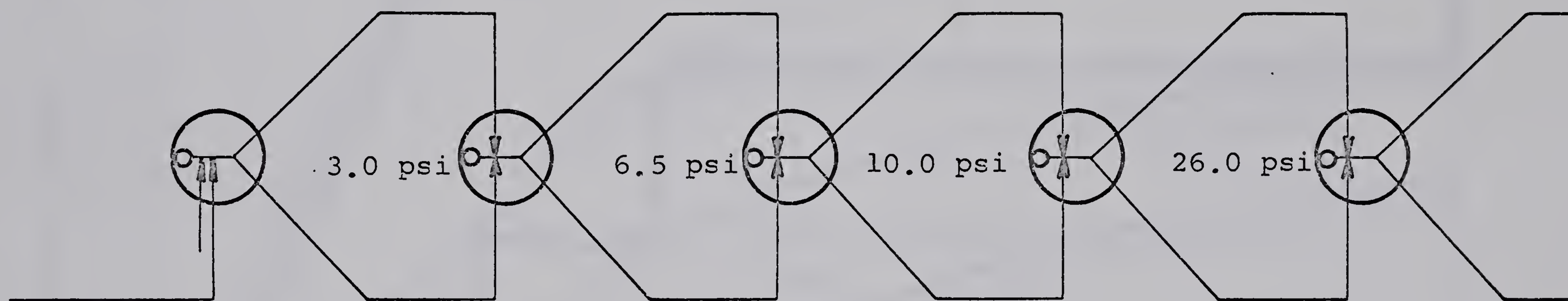


Fig. 3.15 Final Design of Power Pulse Amplifier

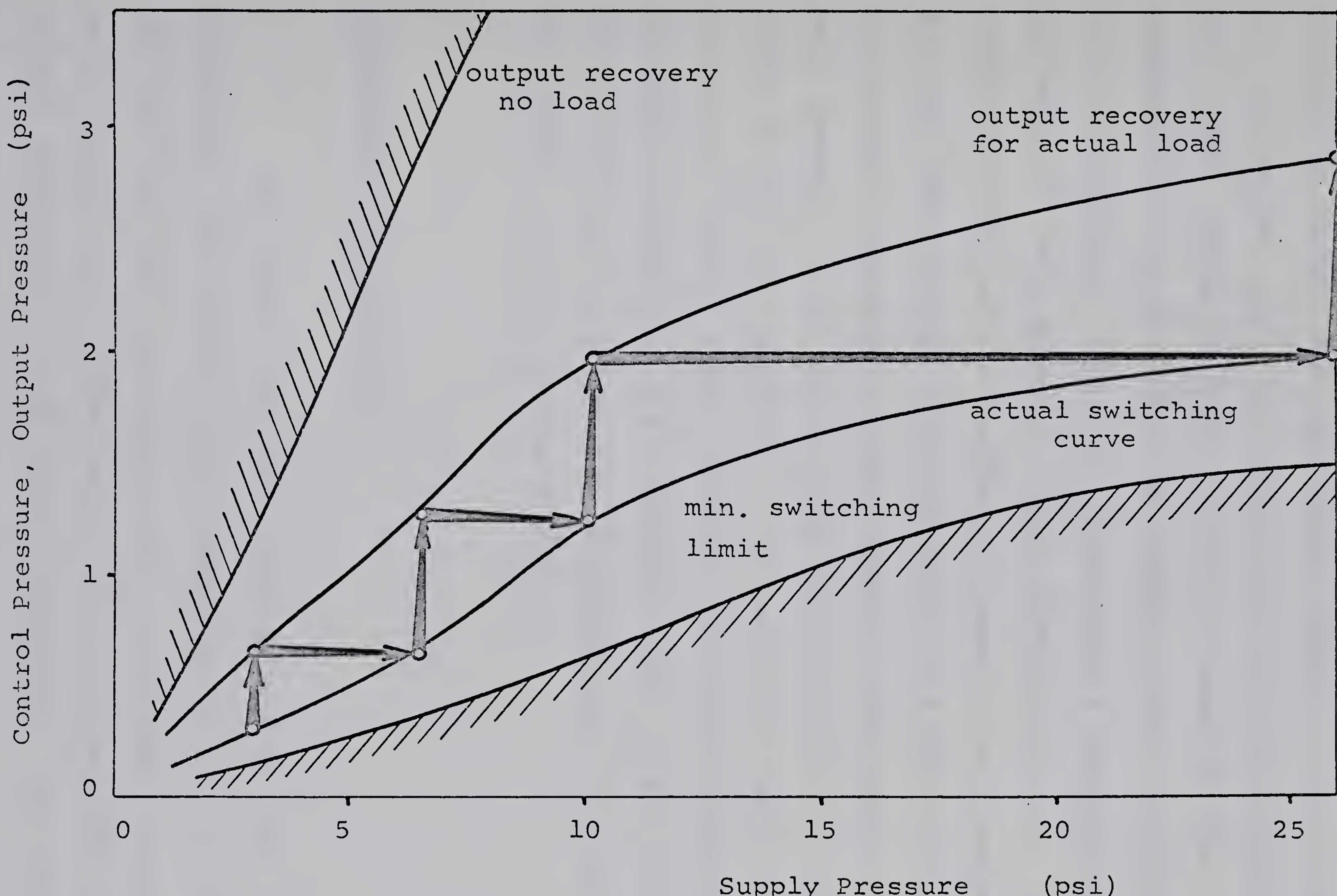


Fig. 3.16 Design of Power Pulse Amplifier

of required stages are readily determined. The required load of each amplifier is provided by the input impedance of the succeeding device. The last stage, however, is not loaded in this manner. Here, one output is loaded by a restrictor and vented, while the other output is loaded by the forward impedance of two Fluidonics No.300282 diodes in series with a restrictor. These two diodes form a separator which prevents the back pressure effect from occuring. As the repetition frequency of pulses increases, the pressure in the tank (the fluidic capacitor which is a part of the integrator) increases. If the separator were omitted, the back pressure effect would cause malfunctions of the last stage of the pulse amplifier. The restrictor connected in series with the diodes provides the proper impedance matching. Mismatching has a serious effect on the shape of the pulses being fed into the integrator and therefore on the proper operation of the integrator.

## Integrator and Comparator

The pulses from the amplifier are fed into an integrator. The output of the integrator is a d-c pressure of which the level is proportional to the power delivered at its input, or, in other words, to the repetition frequency and, therefore, to the sensed temperature. The integrator is a single stage RC circuit as shown in Fig. 3.17.

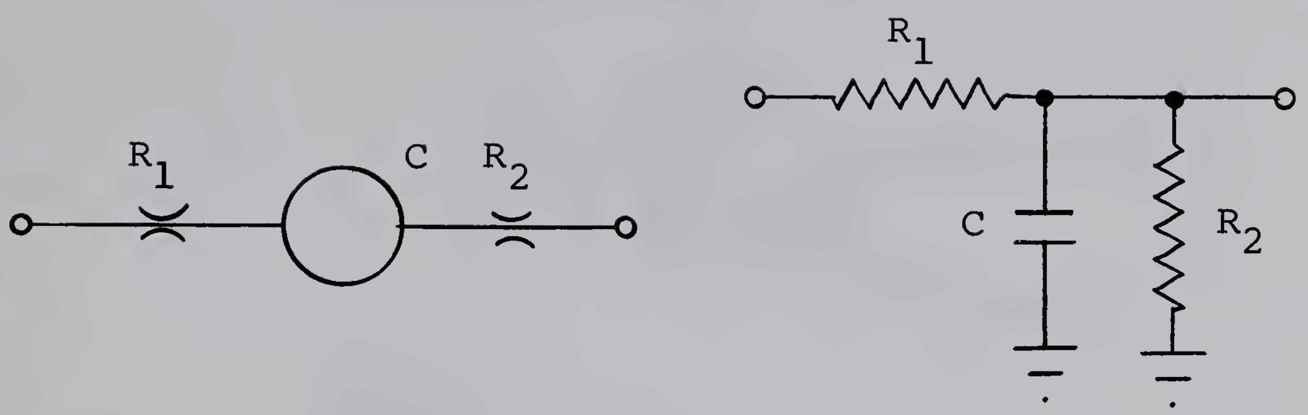


Fig. 3.17 Integrator and Its Electrical Analog

The tank has a volume of 535 $cm^3$ (= 32.4 $in^3$) and the average pressure in the tank is 5 psi. This gives a capacitance of 6.45 CU. The restrictor $R_1$ is 0.5 RU and the restrictor $R_2$ is the input resistance of the Schmitt trigger and it has a magnitude of 1 RU. The calculated time constant of this configuration is then 2.14 sec. Under normal operation the number of pulses delivered into the integrator is in the range of 10 to 45 pulses per second and the time constant of the RC circuit is sufficiently long to ensure proper filtering for smooth d-c output even at the lowest input pulse rates.

A Corning Glass Works Schmitt trigger serves as a comparator, as shown in Fig. 3.18.

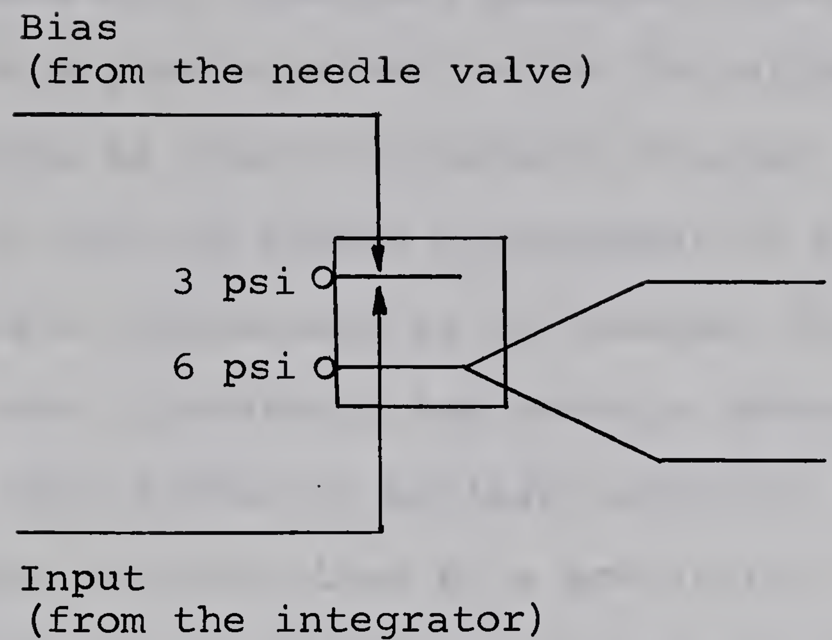


Fig. 3.18 Schmitt Trigger as Comparator

Use of the Schmitt trigger device allows one to consider the temperature control system as operating in the on-off or relay mode. Equivalent electrical or electromechanical systems are normally considered as operating in the on-off or relay mode if less than 1% of the operating range of the sensor is required to change the output state completely from fully on to fully off and vice- versa.

A d-c pressure proportional to the sensed temperature is introduced into one input of the Schmitt trigger and a biasing d-c pressure pre-adjusted to a value corresponding to the desired pre-set temperature is introduced at its second input. As soon as the temperature dependent pressure exceeds the bias pressure, the trigger switches to the on state. It switches back to the off state as

soon as the temperature dependent pressure falls below the bias pressure by a predetermined amount. The difference in input pressures at which the Schmitt trigger switches to the on and to the off states corresponds to Schmitt trigger hysteresis. Hysteresis is an inherent trigger property. In this case, hysteresis has certain advantages in that it causes this system to be less sensitive to noise. The bias pressure is controlled by a precission needle valve, whose dial can be calibrated in degrees centigrade as shown in Fig. 3.19, ( once all components and conditions of the system are permanently adjusted).

## Actuator

The actuator is the only part of the whole system employing components with moving parts. The outputs of the comparator are powerful enough to drive two pressure- to-pressure relays which, in turn, drive the piston of a mechanical valve which opens or shuts off the supply of gas to the burner. The burner is a Bunsen burner modified so that the supply of air is manually controllable. Air is, in this case, supplied permanently and only the supply of gas is controlled by the output of the comparator. The pilot flame guarantees reliable ignition.

In Fig. 3.20 the complete schematic diagram of the regulator is shown and in Fig. 3.21 an overall view is shown.

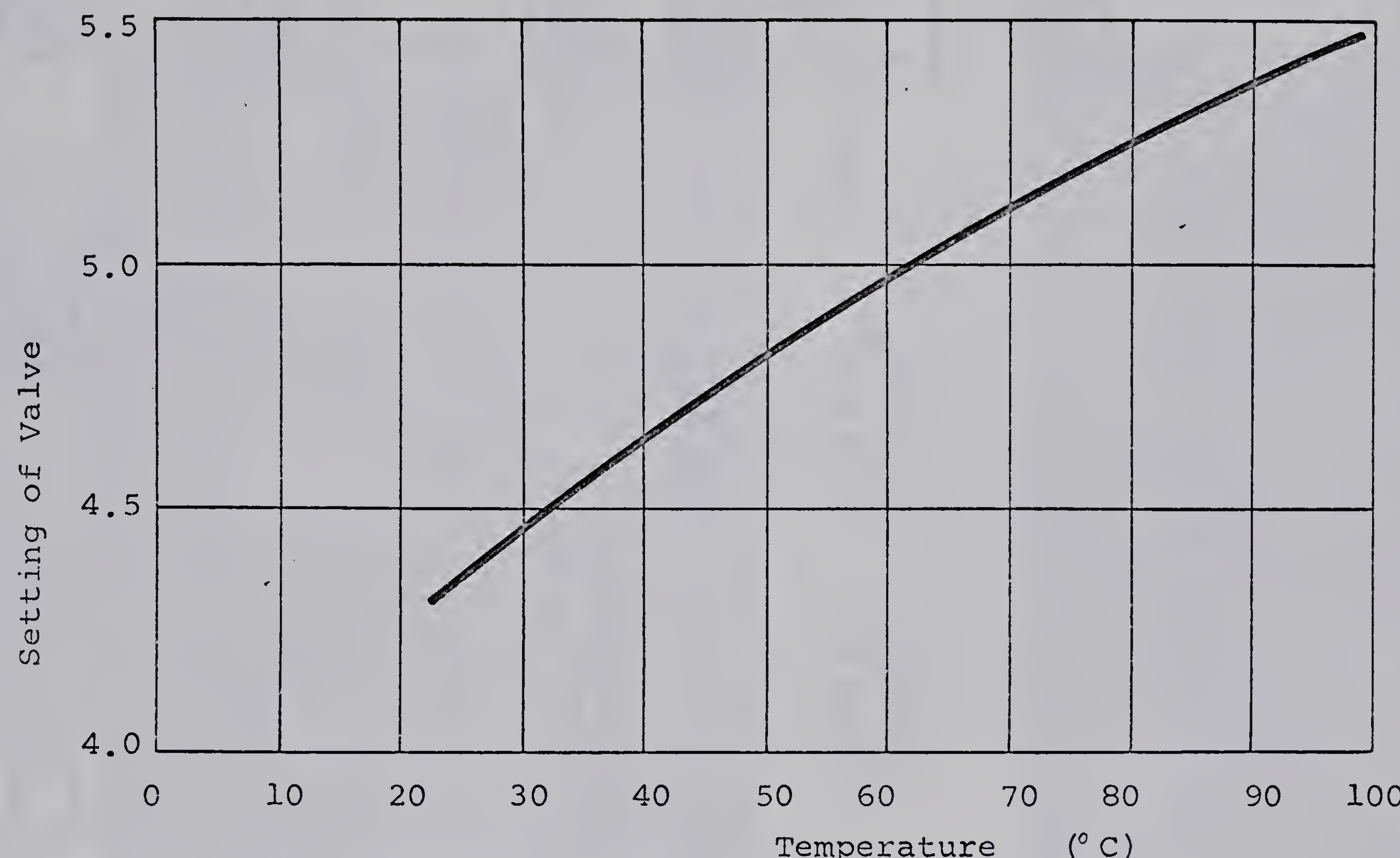


Fig. 3.19 Calibration Curve of Precise Needle Valve

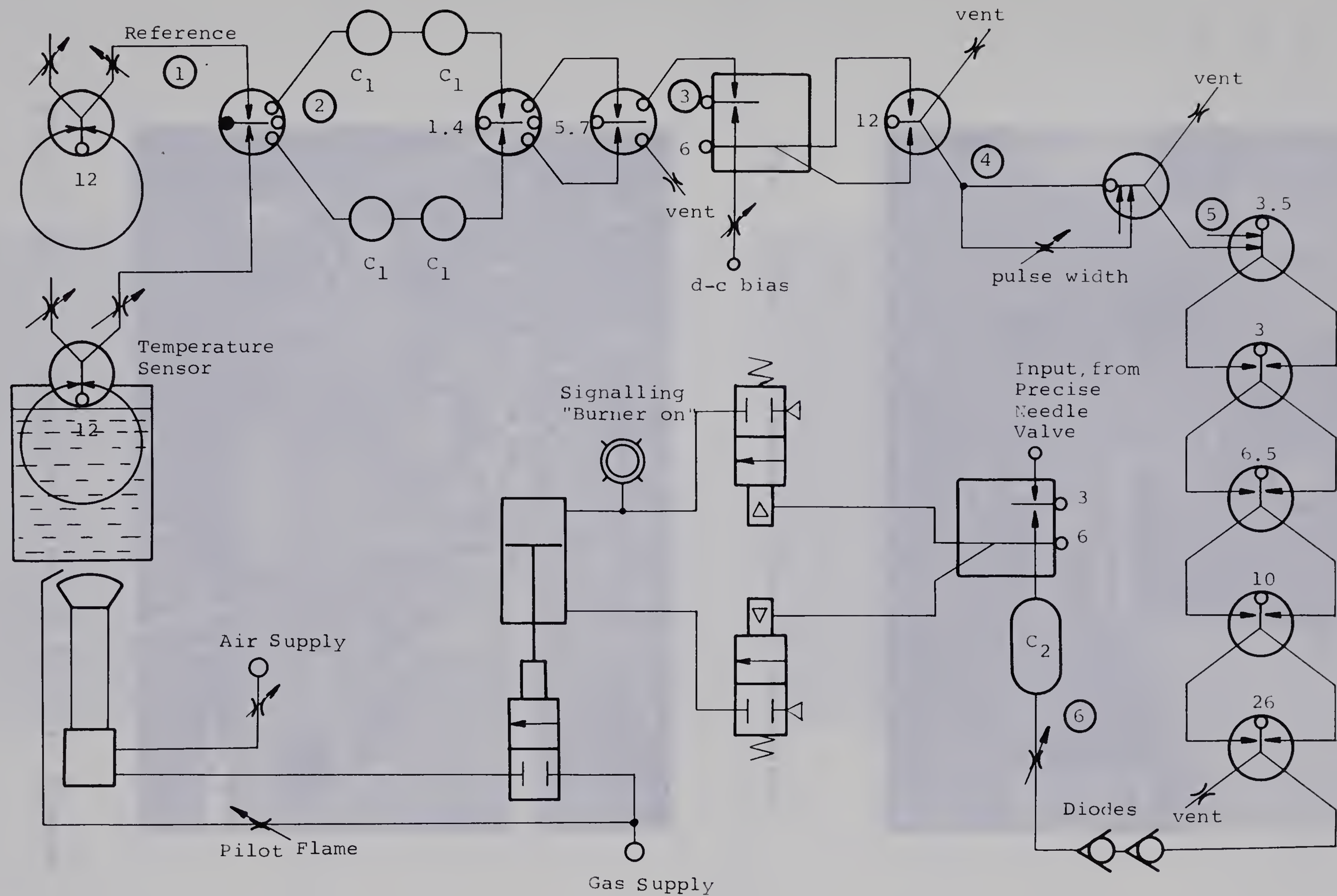


Fig. 3.20 Schematic Diagram of Complete System

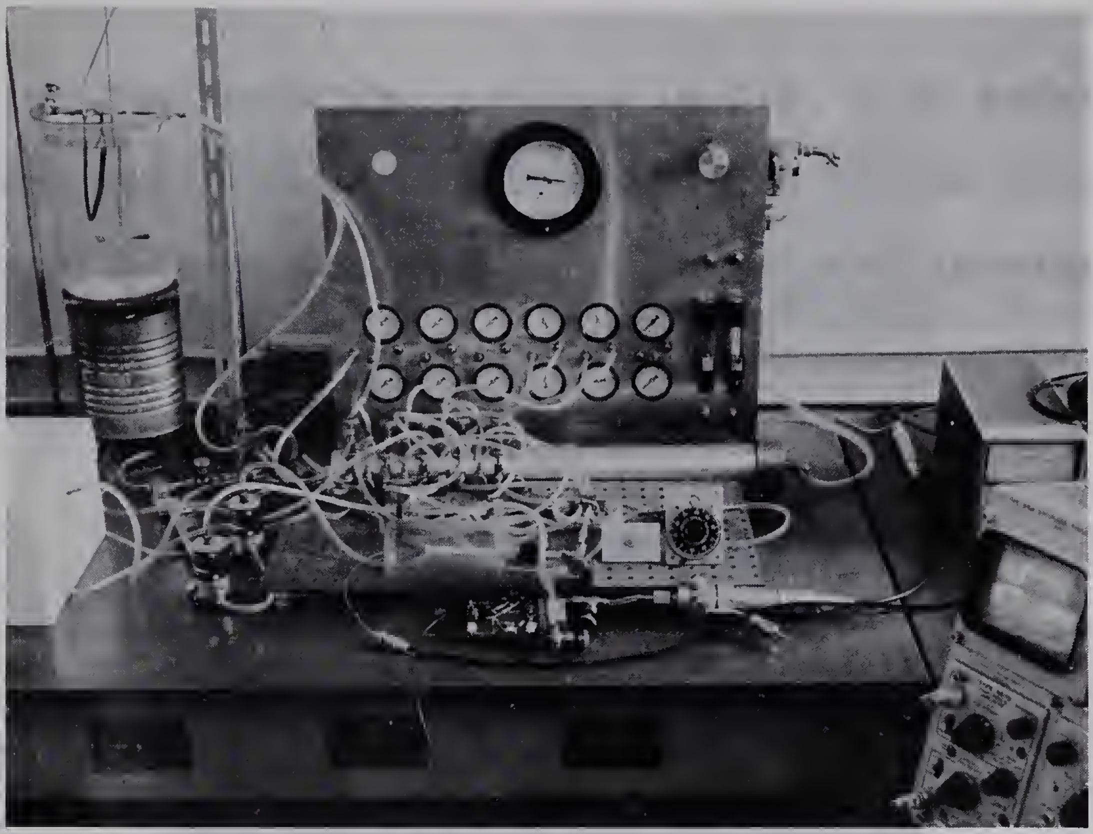

Fig. 3.21a Overall View of Regulator

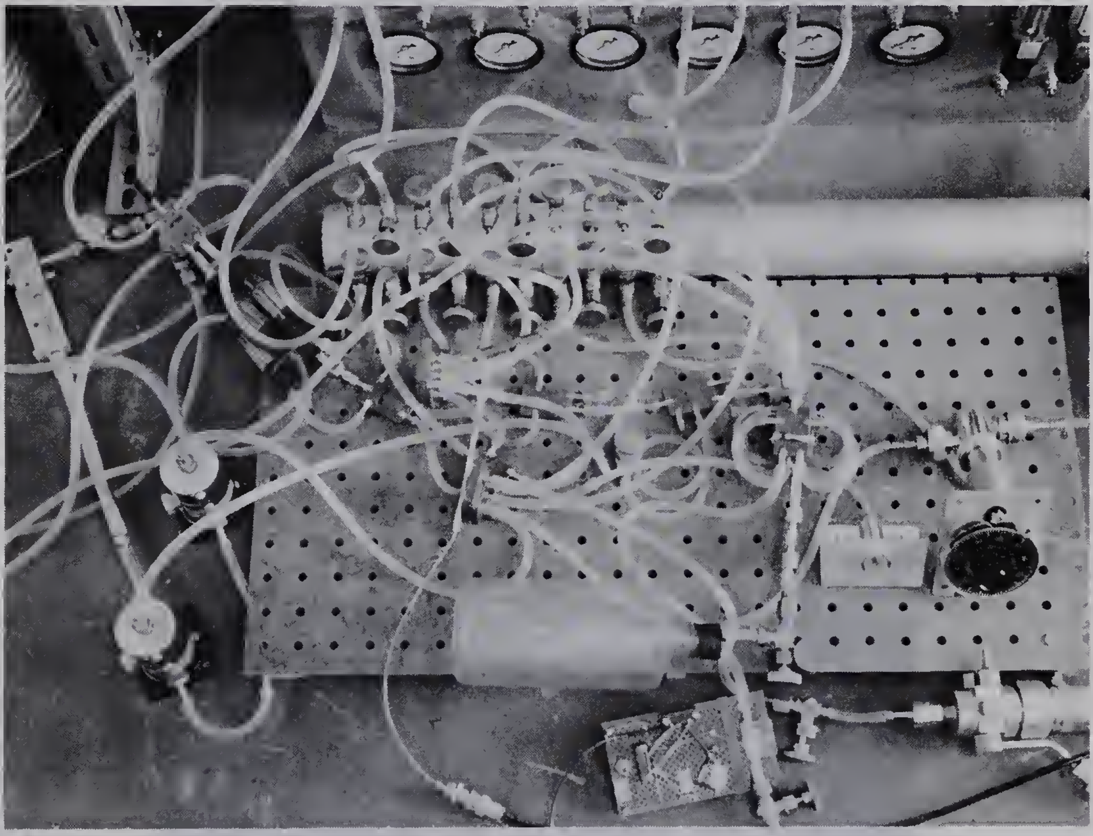

Fig. 3.21b Detailed View of Fluidic System

The encircled numbers in Fig. 3.20 refer to waveforms which appear at these points of the circuit. The actual waveforms are shown in the oscillograms of Fig. 3.22 through to Fig. 3.27.

1

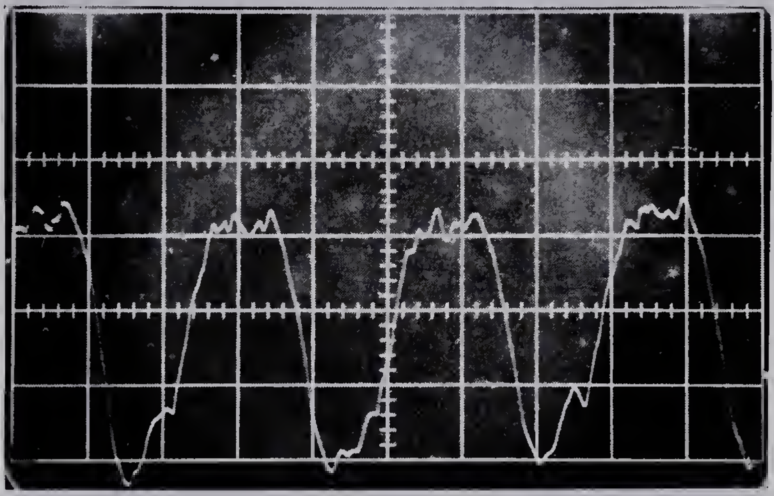

Fig. 3.22 Output of Sonic Oscillator (1 msec/cm;0.2V/cm)

2

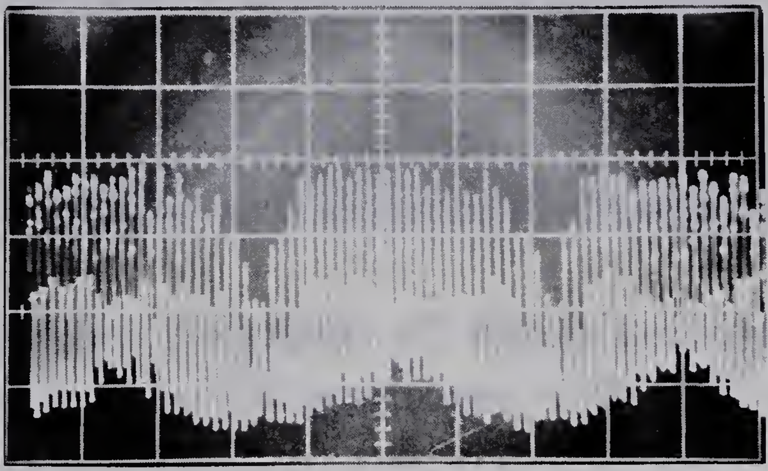

Fig. 3.23 Output of Beat Frequency Detector
(Corresponds to Fig. 3.8b; 20 msec/cm;0.2V/cm)

3

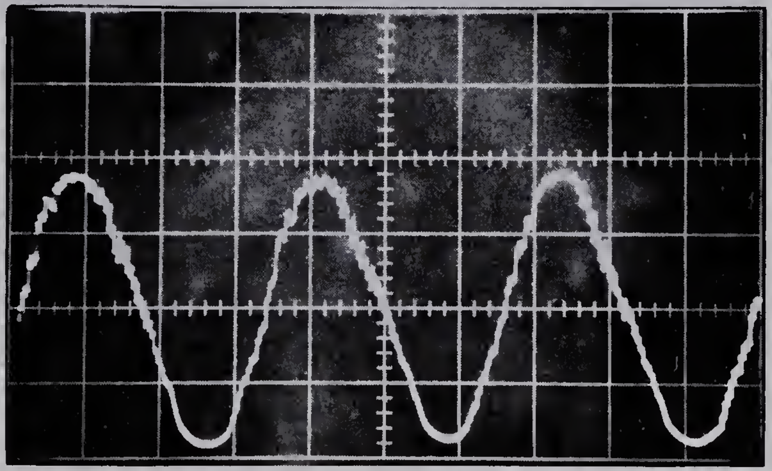

Fig. 3.24 Beat Frequency Signal
(Corresponds to Fig. 3.8c; 20 msec/cm;0.2V/cm)

4

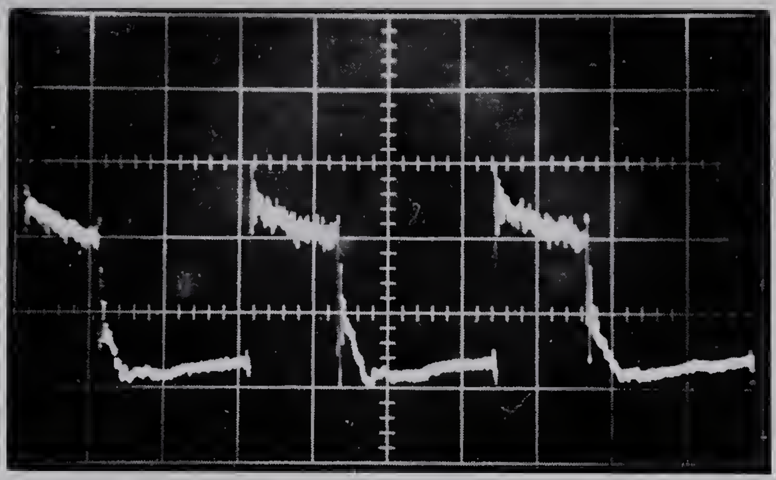

Fig. 3.25 Square Wave Signal (20 msec/cm; 0.5V/cm)

5

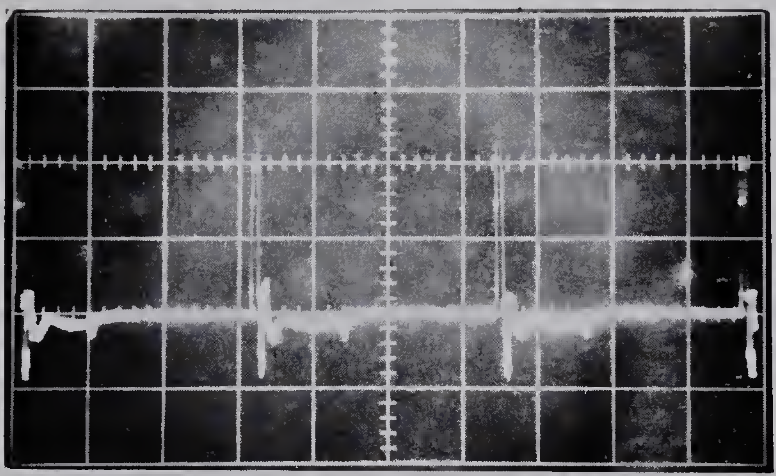

Fig. 3.26 Output of Pulse Generator
(20 msec/cm; 0.2V/cm)

6

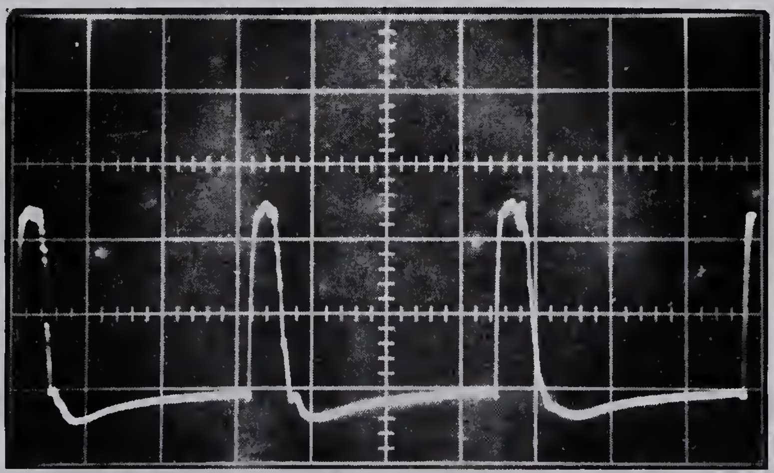

Fig. 3.27 Constant Power Output Pulses
(20 msec/cm; 0.5V/cm)

Experimental Results

A set of measurements was performed on the complete system to verify calculated results and other aspects such as long run operation and sensitivity to mechanical vibrations. The characteristic of major interest was the step response. A step change of input was simply produced by re-adjusting the input (precise needle valve) to a new setpoint temperature, for example from 31 degrees centigrade to 82 degrees centigrade. The measured step response is shown in Fig. 3.28 , which shows that there is actually no overshoot according to properties of the on-off system of the first order. The deviations from the set point are less than 0.5 degrees centigrade and appeared to be smaller than expected.

The next measured characteristic was the effect of a disturbance. In this case, a sudden water temperature change was introduced as a disturbance. The reaction of the regulator in order to bring the temperature of the water back to the pre-set temperature was observed and is shown in Fig. 3.29.

A continuous test run was performed. During 53 hours of continuous test, changes of input as well as disturbances and mechanical vibrations were introduced several times. The system worked well and no malfunctions occured.

## Conclusion

A design philosophy as well as a step by step design procedure was presented in this thesis report. This was done since the design procedure given appears to be directly applicable to other design objectives such as a different temperature regulator range or a different method of sensor installation.

The final industrial temperature regulator design along the principles of this thesis could be integrated into one ceramic or metal block, which would reduce the size and, undoubtedly, improve further the performance of the regulator.

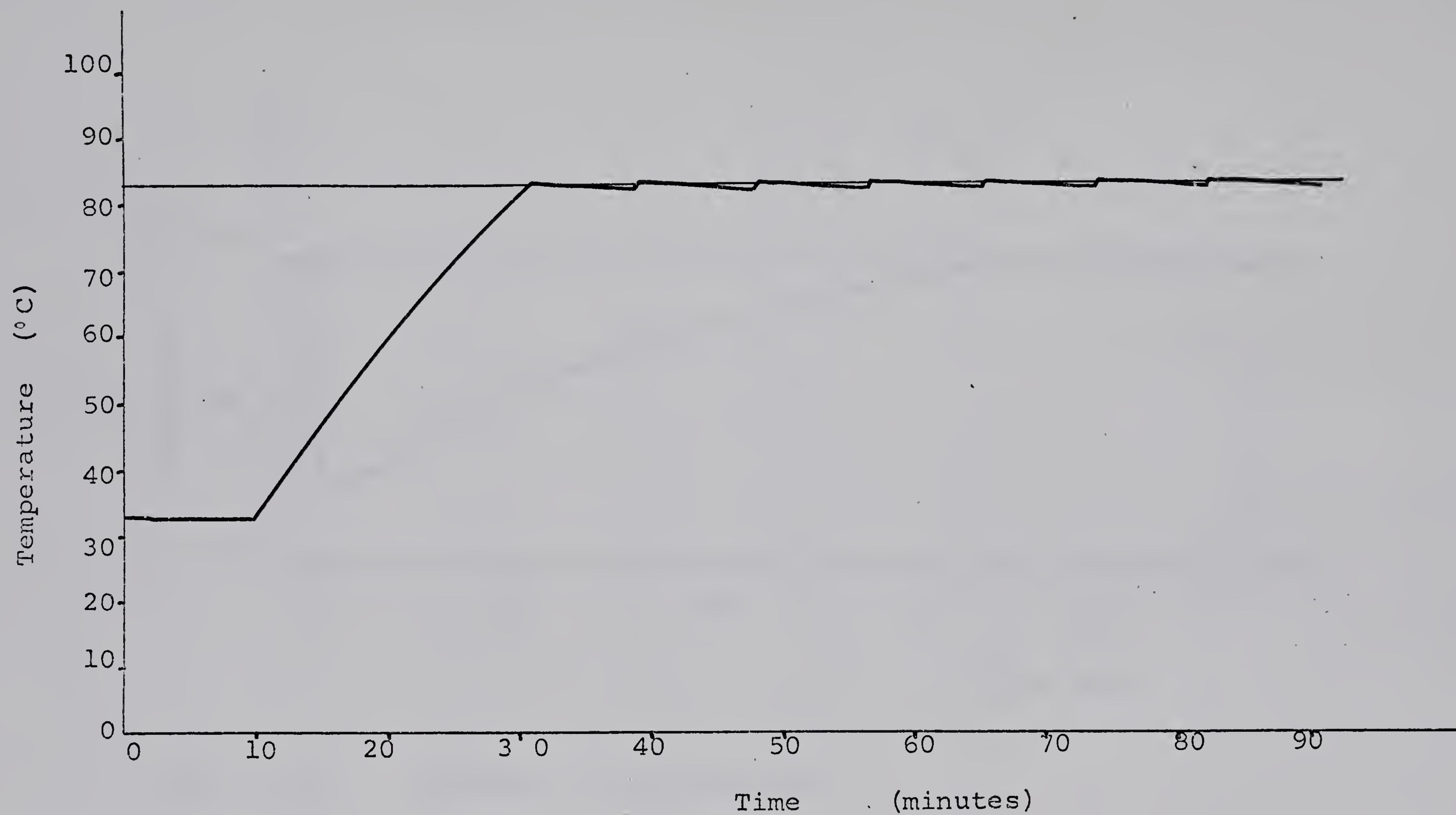


Fig. 3.28 Step Response

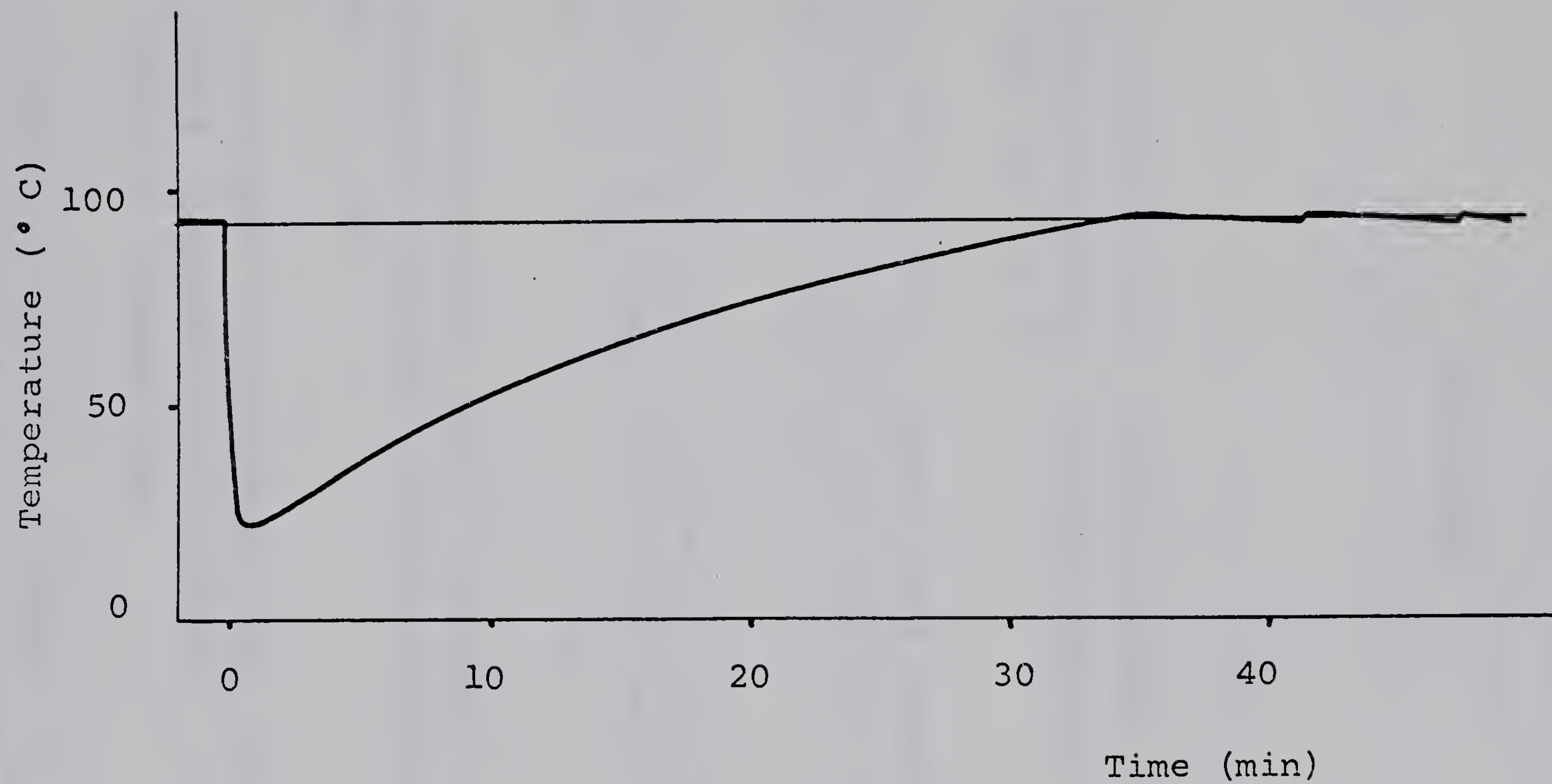


Fig. 3.29 Response to Disturbance

## REFERENCES

1. C.A.Belsterling, "Fluidic Component Description and System Synthesis," Fluidic Quarterly, Vol.1,No.3, 1968, pp. 9 - 32.

2. C.A.Belsterling, "Digital and Proportional Jet Interaction Devices and Circuits," Fluidics Quarterly, Vol.1,No.2, 1968, pp. 54 - 75.

3. C.A.Belsterling, "A Systematic Approach for Designing Fluidic Systems," Control Engineering, April 1966, pp. 63 - 68.

4. C.A.Belsterling, "Analyzing Proportional Fluid Amplifier Circuits," Control Engineering, August 1965, pp. 87 - 92.

5. C.A.Belsterling, Ka-Cheung Tsui, "Analyzing Proportional Fluid Amplifier Circuits," Fluid Amplification Symposium, October 1962.

6. D.C.Berg, W.A.Boothe, L.R.Kelly, D.E.Uehling, "Fluidics Has a Future in Jet Engine Control," Control Engineering, July 1966, pp. 81 - 87.

7. R.L.Bloster, "Proportional Control Systems in Industry," Wescon Journal, No.4, 1967, sec.11/4.

8. F.Folland, "Fluidic Density Measurement," Instruments & Control Systems, April 1968, pp. 97 - 99.

9. H.L.Fox, "Fluidic Device Testing," Wescon Journal, No.4, 1967, sec.11/3.

10. R.N.Gottron, W.Gaylord, "A Temperature Control System Using Flueric Components," Proceedings of the Third Amplification Symposium, Vol.III., Harry Diamond Laboratories, Washington D.C., October 1965, pp. 245 - 265.

11. W.G.Gulland, "A Fluidic Integrator," unpublished Master's dissertation on Department of Electrical Engineering, University of Alberta, June 1967.

12. R.W.Henke, "Applications of Fluidics," IEEE Transactions on Industry and General Applications, Vol.IGA-4,No.5, Sept./Oct. 1968, pp. 490 - 500.

13. R.K.Krishnaiyer, "Fluidic Transmission Line Properties," Instruments & Control Systems, October 1968, pp. 93-96.

14. J.M.Kirshner, "Fluid Amplifiers." Mc Graw-Hill Book Company, 1966.

15. L.R.Moore, R.F.Turek, "Fluidic Time Optimal Adaptive Control System," Wescon Journal, Vol.4, 1967, sec.11/1.

16. W.T.Rauch, "Putting Fluidics to Work," Fluidic Quarterly, Vol.1.,No.1, 1968, pp. 78 - 84.

17. J.N.Shin, W.A.Boothe, "Connecting Elements into Circuits and Systems," Control Engineering, September 1964, pp. 86 - 93.

18. C.E.Spuropoulos, "A Sonic Oscillator," Proceedings of the Second Harry Diamond Laboratories Fluid Amplification Symposium, Vol.II, pp. 27 - 52, May 1964.

19. "Fluidics Find Practical Use in Machine Control," Product Engineering, April 11, 1966.

# APPENDIX A

## FLUIDIC ACTIVE DEVICES

The fluidic devices used in this project were manufactured by Corning Glass Works except for fluidic diodes, indicators and needle valves which were Fluidonics products. The device properties of greatest concern are presented below in the form of measured characteristics.

### The Jet Deflection Amplifier

There are two types of jet deflection amplifiers available, both of them capable of serving to amplify analogue signals. The first one is a centre dump jet deflection, or proportional, amplifier, which remains stable under all loading conditions. The second one is the non centre dump jet deflection amplifier, which has higher gain but becomes unstable if not sufficiently loaded. Usually, a combination of both types offers the best solution.

Using the jet deflection amplifiers to build amplification blocks of several stages,the first problem to be solved is the static matching and supply pressure calculation. Since fluidic amplifiers are rather nonlinear devices, the best tool for performing of the required calculations is the use of characteristics. The input and output characteristics provide complete information as far as the staging is concerned. These characteristics as measured are presented below in Fig. A.1 through to Fig.A.6.

## The Wall Attachment Amplifiers

Wall attachment amplifiers have been used for, basically, two purposes. The first is the sonic oscillator. The second one is their use for pulse amplification. The basic characteristics describing the bistable devices needed for staging have been presented in Fig. 3.16.

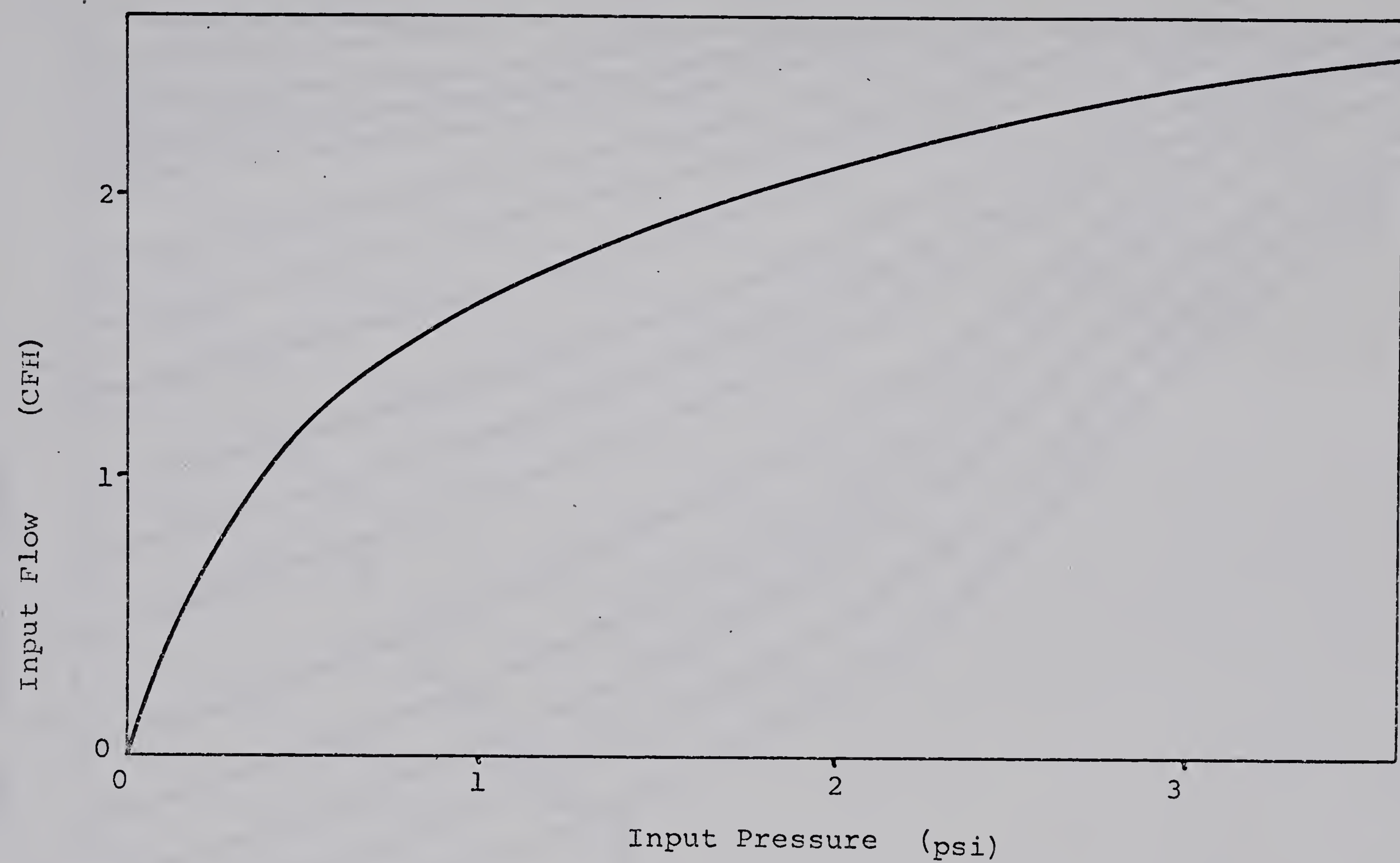


Fig. A.1 Input Characteristic of Centre-Dump Proportional Amplifier

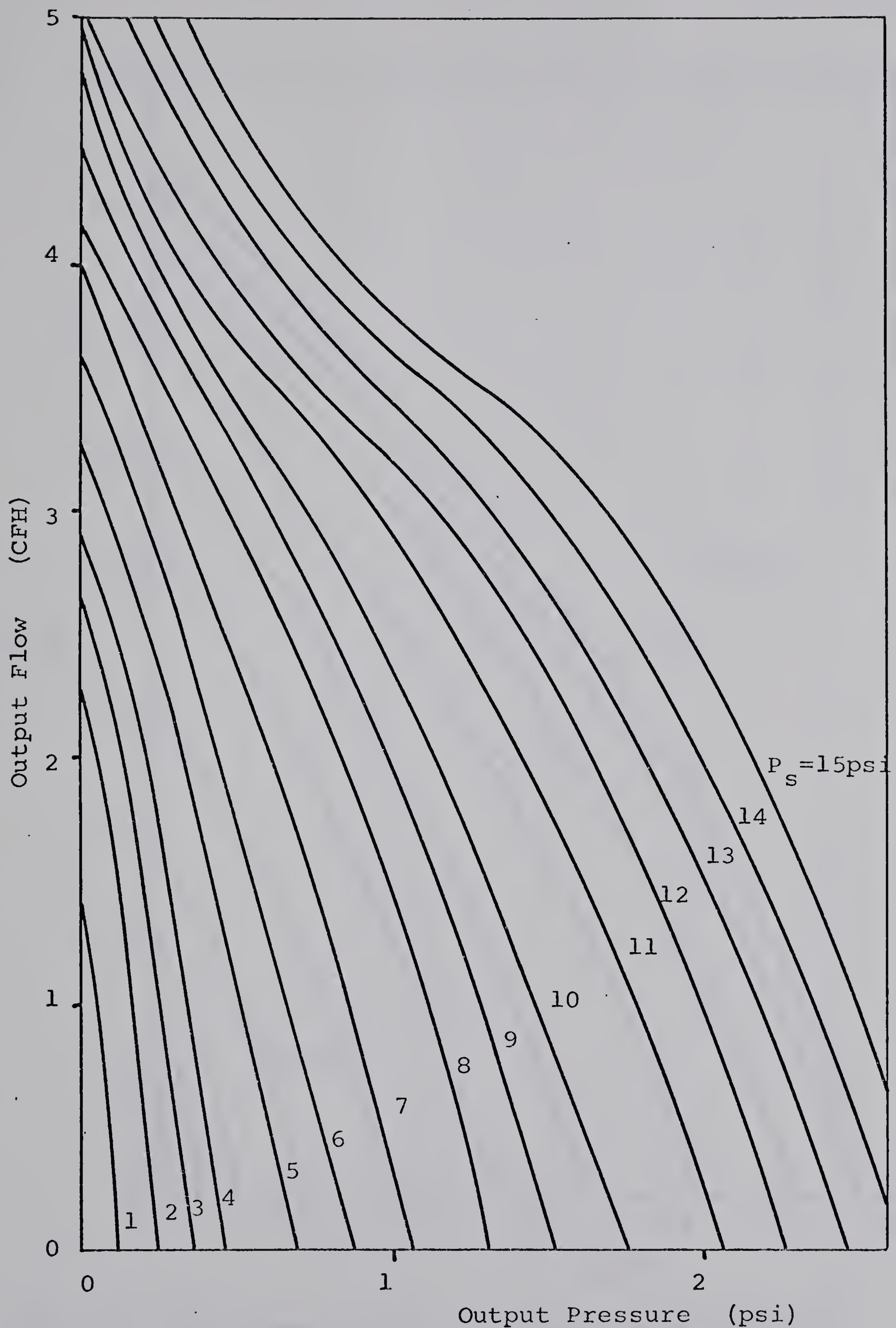


Fig. A.2 Output Characteristics of Centre-Dump Amplifier

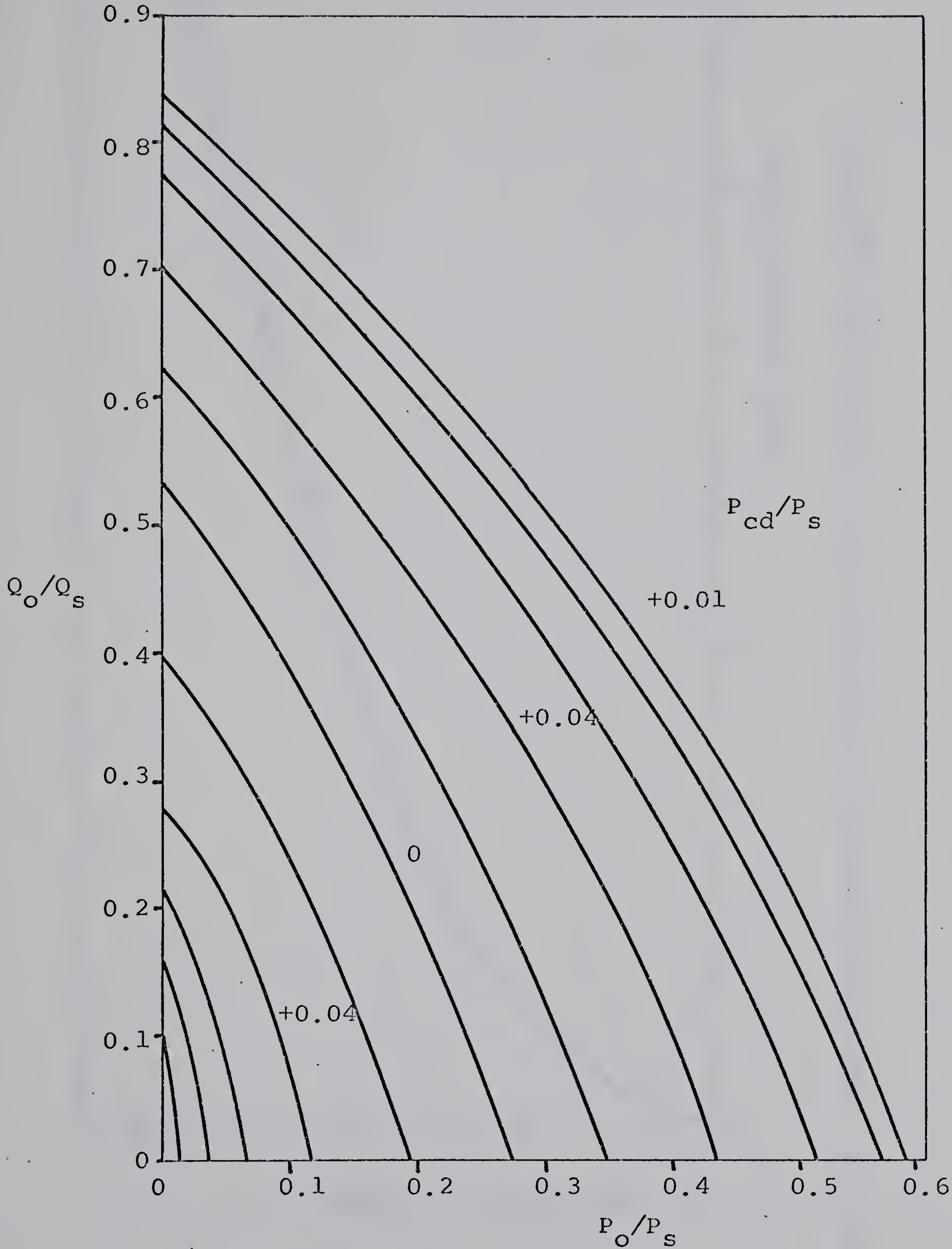


Fig. A.3 Non-Dimensionalized Output Characteristics of Centre-Dump Proportional Amplifier

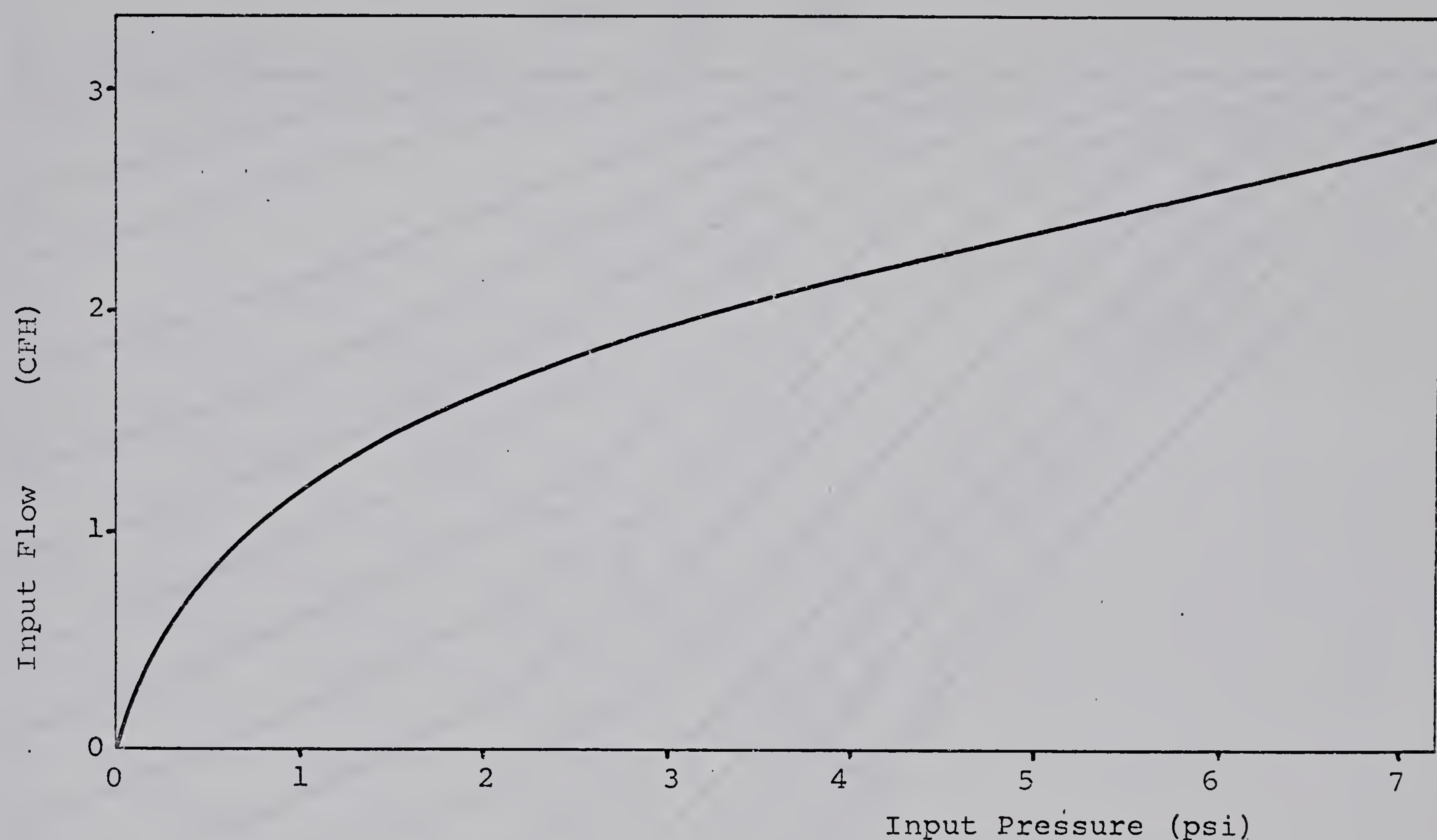


Fig. A.4 Input Characteristic of Non-Centre-Dump Proportional Amplifier

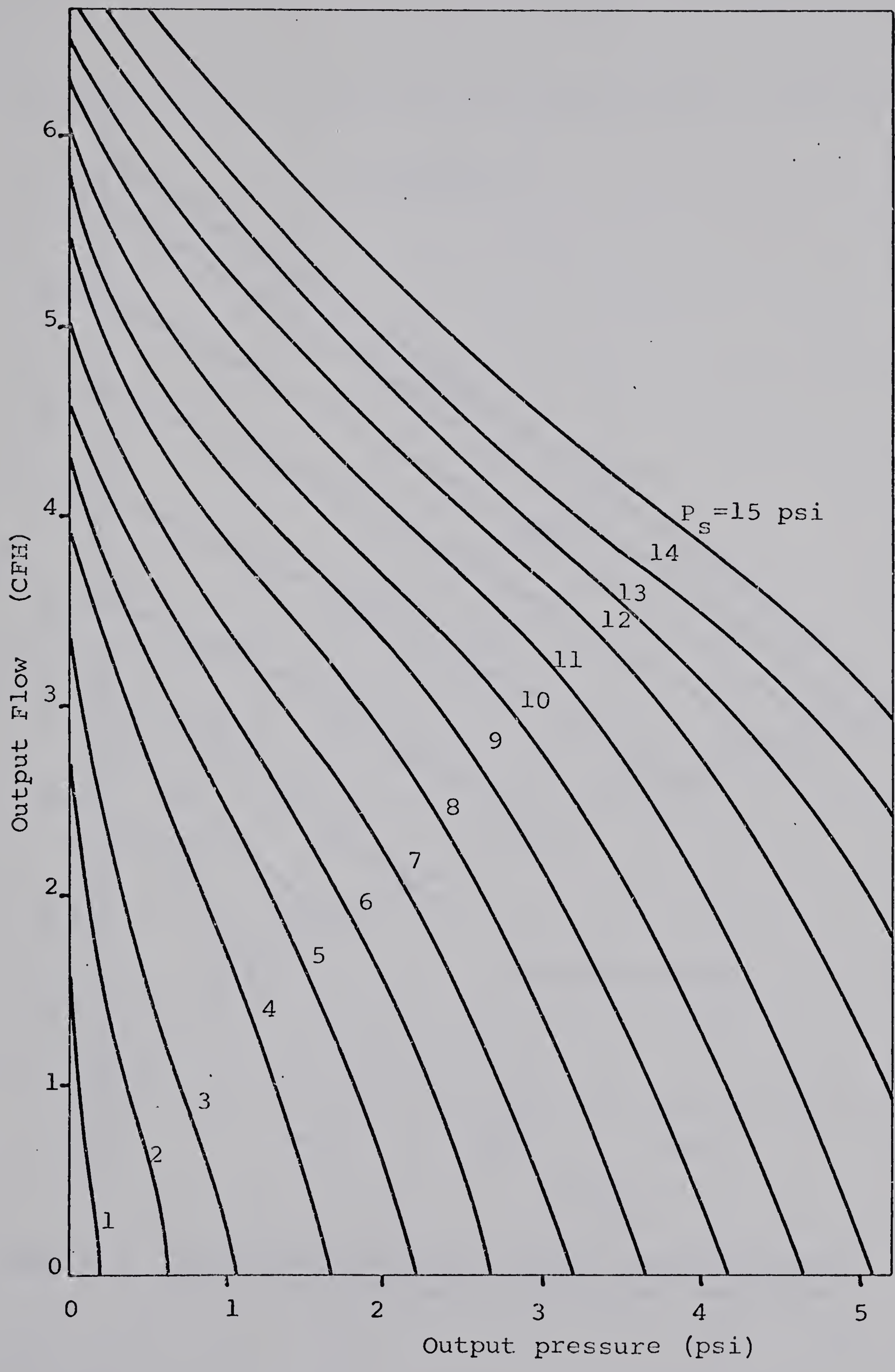


Fig. A.5 Output Characteristics of Non-Centre-Dump Proportional Amplifier

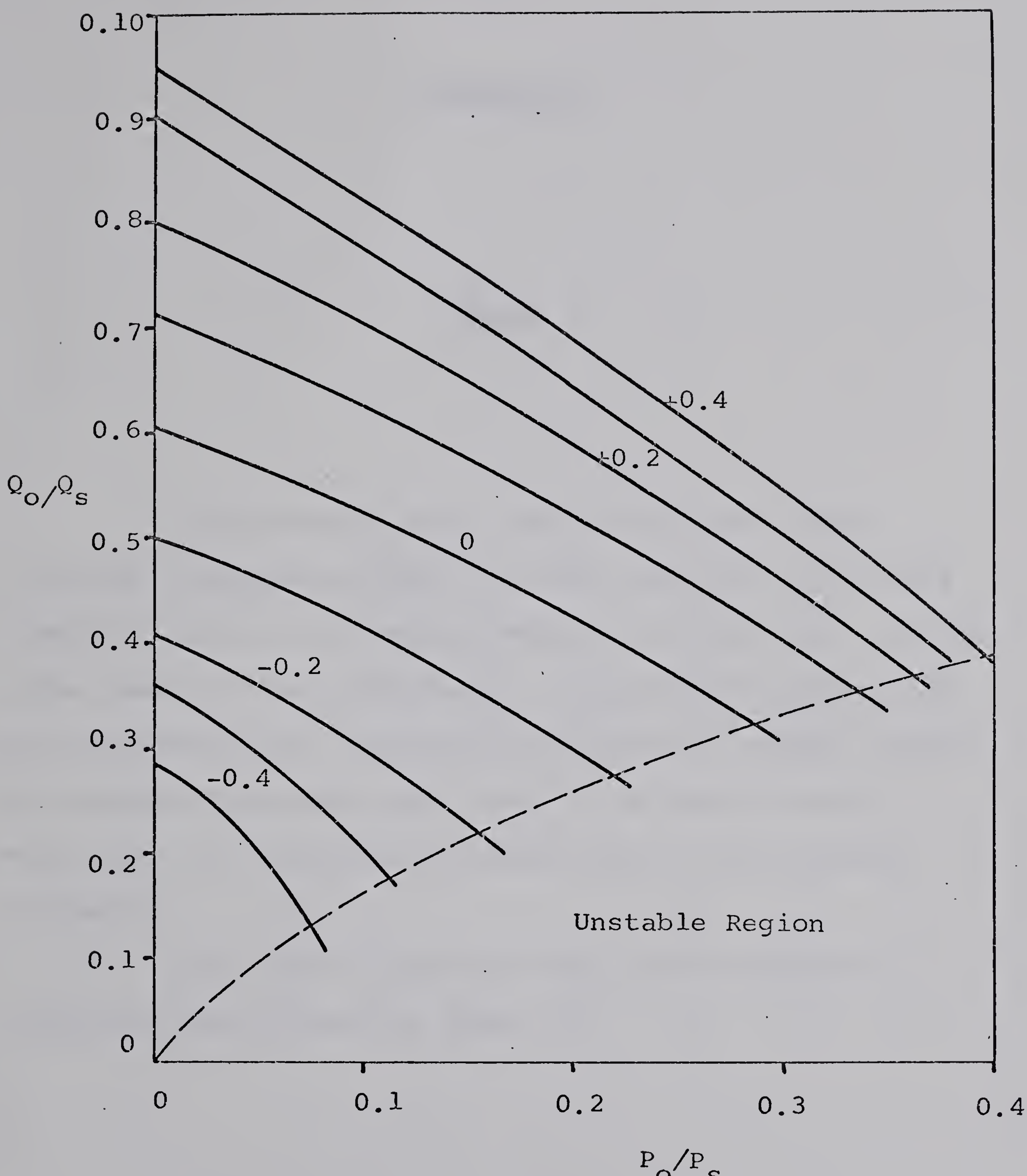


Fig. A.6 Non-Dimensionalized Output Characteristics of Non-Centre-Dump Proportional Amplifier

# APPENDIX B

## UNITS

The system of units used in fluidics is distressingly nonstandardized. In those parts of this thesis concerned mainly with physics MKSA units were used. On the other hand, in the parts deling with practical properties and considerations practical units such as inches, pounds and degrees Fahrenheit were used. In no case, however, were units from different systems mixed, thus avoiding confusion.

The circuit quantities and their respective units are listed below in Table 3.

| Quantity | Electrical Equivalent | Unit | Abbreviation |
|---|---|---|---|
| Pressure | Potential | $lb / in^2$ | psig |
| Differential Pressure | Potential Difference | $lb / in^2$ | psid |
| Flow | Current | Standard Cubic Inches/Second | scis |
| | | Standard Cubic Feet/hour | scfh |
| Mass | Charge | Standard Cubic Inches | sci |
| Resistance | Resistance | $lb\ sec/in^5$ Resistance Unit | RU |
| Capacitance | Capacitance | $in^5 / lb$ Capacitance Unit | CU |
| Inductance | Inductance | $lb / in^5$ Inductance Unit | IU |

Table 3 Circuit Quantities and Their Units